PUBLIC ROADS

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BUREAU OF PUBLIC ROADS

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OIL STAINS ON A CONCRETE ROAD WHICH INDICATE THE LINES OF MAXIMUM TRAFFIC

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TRANSVERSE DISTRIBUTION OF MOTOR VEHICLE TRAFFIC ON PAVED HIGHWAYS

By J. T. PAULS, Associate Highways Engineer, United States Bureau of Public Roads

A LIMITED investigation conducted recently by the Bureau of Public Roads for the purpose of determining the transverse distribution of traffic on paved highways, has developed a number of very significant facts with respect to the effect of road width, curves, shoulder conditions, grades, crown of surface and other physical factors on the distribution of the traffic laterally. Although the investigation has not been sufficiently extensive to develop relations definite enough to describe as the laws of lateral distribution, the observations made are highly interesting and of immediate practical value, with respect to highway design and traffic regulation. Previous traffic surveys[1] have given the net and segregated tonnages and the number of applications of the load per unit of time, but so far as is known, this is the first attempt to establish the transverse distribution of traffic on pavements.

LOCATION AND CHARACTER OF INVESTIGATION

The observations were made in the vicinity of Washington, D. C., and locations were selected which were considered to be representative of the several conditions it was desired to study. At each point selected, the paved width was marked with paint into 1-foot sections. The right rear wheel passages in each direction were noted by different recorders with tally registers. The known distance between the wheels was utilized to add to the register the left wheel passages. The observations represent the total rear wheel passages considered as the sum of the traffic in both directions.

The truck and passenger traffic were registered separately and each considered as 100 per cent in plotting the graphs. Trucks of less than 2 tons capacity were not counted with the heavier types; because it was believed that such trucks would be equivalent to passenger cars.

The quantitative results obtained from the investigation are shown on the accompanying charts. The percentage of traffic passing over any 1 foot of width is given in terms of the total rear-wheel traffic in both directions, considered as 100 per cent. The average position of the outer wheels, as indicated on the charts, has been determined by locating the center of gravity of the area representing the outer wheel passages only. The corresponding average position of the inner wheels was then located at the known gauge distance from the outer wheels. The distribution of the traffic moving in the two directions is represented by the ordinates of the shaded and unshaded areas. The sum of the total ordinates at the 1-foot divisions represents the total traffic moving in both directions considered as 100 per cent. The average net clearance between vehicles moving in opposite directions has been calculated from the computed average location of the outer wheels on the basis of what appears to be the average overall width of vehicles. For passenger cars this overall width is taken at 5.7 feet, which is practically a constant for all makes of cars. For trucks a width of 7.3 feet has been used. If the maximum legal width of 8 feet obtaining in a number of States were used, the average truck clearances shown on the charts would be reduced accordingly. Figure 1 shows the dimensions used. The highway conditions at each of the points of observation are shown by the photographs accompanying the charts; and are tabulated and the results further described in Table 1.

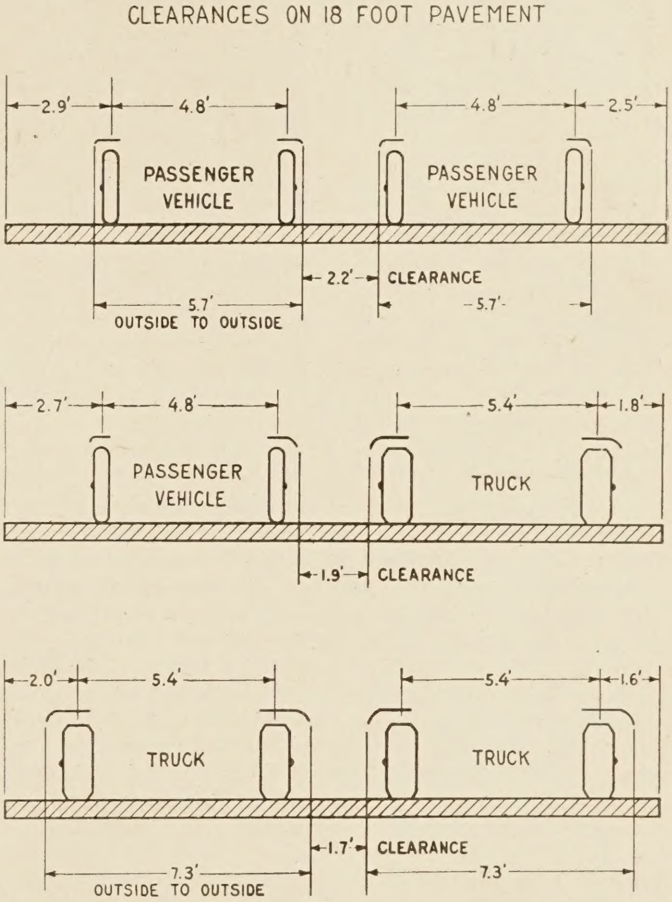

FIG. 1.—Dimensions of passenger vehicles and motor trucks assumed for the purpose of computing average clearance, and clearances on an 18-foot pavement under three conditions of traffic (based on data from test 4, Fig. 5)

SUMMARY OF FINDINGS

The principal results of the observations with respect to the distribution of traffic and the effect of various physical conditions are as follows:

Pavement width.—It seems to be definitely established that 18 feet is the minimum pavement width which will permit passenger vehicles and trucks driven in the preferential position to pass in safety and with a reasonable amount of clearance. Trucks have almost as much clearance as passenger cars, because the former are habitually driven about 1 foot closer

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[1] See Public Roads, Vol. 5, No. 1. March, 1924. Connecticut Highway Transportation Survey, p. 14, and Vol. 5, No. 10, December, 1924. Highway Traffic in California, p. 12.

Table 1.—*Data showing conditions on various pavements and distribution of motor-vehicle traffic*

Test No.	Type of vehicle	Pavement type	Crown	Super-elevation	Average speed	Condition of shoulders		Other features		Width of pavement	Traffic line	Grade		Horizontal curve			Average distance of wheel from edge		Average clearance	Maximum traffic from one wheel		
						Left	Right	Left	Right			Left	Right	Degree	Length	Direction right side	Left	Right		Left side	Right side	On pavement
			In.	*In.*	*Miles per hr.*					*Ft.*		*Per cent*	*Per cent*	° ′	*Feet*		*Ft.*	*Ft.*	*Ft.*	*Per cent*	*Per cent*	*Per cent*
1	Passenger	Concrete	2¼	----	25	Bad	Bad	----	----	18	----	----	----	----	----	----	3.5	3.2	0.9	8.1	8.4	11.8
4	do	do	2¼	----	25	Fair	Fair	----	----	18	----	----	----	----	----	----	3.3	2.5	2.2	8.6	10.1	10.9
4	Truck	do	2¼	----	12	do	do	----	----	18	----	----	----	----	----	¾	2.0	1.6	1.6	12.7	8.9	12.7
23	Passenger	Bituminous macadam.	4	----	25	do	do	----	----	22	----	----	----	----	----	----	3.7	3.7	4.2	5.1	6.8	8.1
23	Truck	do	4	----	12	do	do	----	----	22	----	----	----	----	----	----	2.8	2.5	3.9	11.1	4.4	11.1
17	Passenger	Granite blocks.	3	----	18	----	----	Curb	Curb	24	----	----	----	----	----	----	3.3	4.2	6.1	6.7	5.6	7.0
17	Truck	do	3	----	10	----	----	do	do	24	----	----	----	----	----	----	2.3	3.8	5.1	10.2	8.5	10.2
9	Passenger	Bituminous macadam.	3½	----	25	Fair	Fair	----	----	14	----	+2	−2	----	----	----	1.6	2.2	−0.2	10.0	9.7	19.5
7	do	do	7½	----	22	do	do	Ragged edge	Ragged edge	15	----	+2	−2	----	----	----	2.2	3.6	−1.2	9.1	8.5	17.4
7	Truck	do	7½	----	12	do	do	do	do	15	----	+2	−2	----	----	----	1.7	2.8	−2.3	11.2	9.5	20.7
8	Passenger	do	6	----	20	do	do	do	do	16	----	+6	−6	----	----	----	3.0	3.3	−0.7	7.0	13.2	18.2
5	do	do	3¾	----	25	Good	do	(1)	(1)	20	----	−1	+1	----	----	----	4.5	3.2	1.9	8.6	5.5	9.6
5	do	do	3¾	----	30	do	do	(2)	(2)	20	----	−1	+1	----	----	----	3.6	2.1	3.9	7.2	11.0	11.7
5	Truck	do	3¾	----	15	do	do	Ragged edge	Ragged edge	20	----	−1	+1	----	----	----	1.8	1.2	4.2	10.4	11.0	11.7
20	Passenger	Concrete	2¼	----	15	Fair	do	----	----	18	----	+7	−7	----	----	----	3.0	3.3	1.3	7.2	7.2	12.5
10	do	Bituminous macadam.	3¾	----	20	Gutter	Gutter	Rutting	Rutting	20	----	−6	+6	----	----	----	4.1	4.7	0.8	6.6	7.2	10.3
10	Truck	do	3¾	----	10	do	do	do	do	20	----	−6	+6	----	----	----	3.6	3.1	0.5	10.6	7.7	11.6
12	Passenger	do	6	----	20	do	do	(3)	(3)	24	Center	----	----	----	----	----	4.4	4.2	5.0	11.6	6.4	11.6
12	Truck	do	6	----	12	do	do	Rutting	Rutting	24	do	----	----	----	----	----	4.0	4.7	2.5	10.0	8.8	10.0
11	Passenger	Concrete	2¼	----	20	Good	Good	----	----	18	do	−1	+1	----	----	----	2.6	2.6	2.4	10.8	10.8	11.9
6	do	do	2½	----	25	Fair	Fair	----	----	20	do	−2	+2	----	----	----	3.4	3.1	3.1	10.3	7.7	10.7
6	Truck	do	2½	----	12	do	do	----	----	20	do	−2	+2	----	----	----	2.7	2.4	2.1	10.8	15.8	15.8
16	Passenger	Bituminous macadam.	----	9	20	do	Gutter	(4)	(4)	24	do	----	----	18	312	Inner	5.0	3.0	5.6	7.0	7.7	7.7
16	Truck	do	----	9	12	do	do	(4)	(4)	24	do	----	----	18	312	do	4.5	2.5	4.2	7.6	8.6	8.6
19	Passenger	do	----	6	18	Gutter	Fair	----	----	24	do	----	----	20	175	do	3.6	1.7	8.3	8.8	5.6	9.6
13	do	do	----	5	25	Fair	do	----	----	20	----	----	----	15	100	do	4.7	2.2	2.7	6.3	9.2	10.3
13	Truck	do	----	5	12	do	do	----	----	20	----	----	----	15	100	do	2.6	1.4	3.2	9.0	16.7	16.7
14	Passenger	do	----	5	25	do	do	(2)	(2)	20	----	----	----	8	400	Outer	2.4	4.4	2.8	11.2	5.1	12.1
14	Truck	do	----	5	12	do	do	(2)	(2)	20	----	----	----	8	400	do	1.2	3.7	2.3	15.2	6.9	15.2
18	Passenger	do	----	8	25	do	do	----	----	22	----	----	----	11 30	230	Inner	6.0	3.2	2.4	5.4	4.8	10.2
18	Truck	do	----	8	12	do	do	----	----	22	----	----	----	11 30	230	do	5.8	1.9	1.5	4.0	18.0	18.0
22	Passenger	Concrete	----	5	20	do	----	----	Fill and guard rail.	18	----	+2	−2	25	375	Outer	2.2	5.8	−0.4	9.8	4.7	13.7
21	do	Bituminous macadam.	5½	----	22	do	Fair	----	----	22	----	+7	−7	----	----	----	4.2	5.1	2.3	6.4	6.7	12.4
21	Truck	do	5½	----	12	do	do	----	----	22	----	+7	−7	----	----	----	1.7	2.6	4.9	12.3	12.3	13.1
3	Passenger	Concrete	2¼	----	25	Bad	Bad	----	----	18	----	----	----	----	----	----	3.8	4.0	−0.2	9.5	8.5	15.5

[1] Taken at night.

[2] 2½-foot concrete edges.

[3] Bridge abutment.

[4] View obstructed by bank at right.

to the edge of the pavement than the latter. It is interesting to note that drivers of vehicles apparently will sacrifice clearance rather than drive closer to the edge than they instinctively feel to be safe.

In suggesting a minimum width of 18 feet the observations bear out current practice based upon gross observation. A width of 20 feet would apparently permit the passing of vehicles with greater ease and safety and without excessive cost. It is apparent, however, that a width in excess of 20 feet is unnecessary for a two-way pavement on tangents either for trucks or passenger vehicles, since the clearance between the vehicles at their preferred driving position is sufficient on a pavement of this width to permit passing with safety.

That the used width of a pavement may frequently be considerably less than its apparent width is strikingly brought out by several of the observations. In several instances it is shown that the outer foot of the surfaced section is totally ineffective because of a bad shoulder condition, a closely set guardrail, a steep crown, a bad gutter or the ragged edge of a bituminous macadam surface; and in one case a 24-foot pavement has been found to be effectively not more than 20 feet wide because of the abutments of an overhead railroad bridge which are crowded close to the edge of the pavement.

Curves.—The observations provide specific support for the prevailing belief that traffic in general shifts toward the inside edge of the pavement in rounding horizontal curves. At variance with the usual assumption, however, the trucks are found to shift their course toward the inside of the curve less than the passenger vehicles; and under all circumstances the truck drivers are found to adhere more closely to the edges of the pavement than the operators of passenger vehicles.

It is found that traffic moving on the outside of the curve shifts its course farther in the direction of the inside than the traffic moving in the opposite direction, which is limited in its choice of a course by the proximity of the pavement edge. It follows, therefore, that unless the pavement is widened on the curves the normal tangent clearance between the two lines of vehicles will be reduced. The behavior of the traffic on the curves is influenced, however, by the presence or absence of traffic center lines; the amount of superelevation and whether the superelevated section has a plane or crowned surface; the condition of the shoulders and roadsides; the presence or absence of roadside structures such as guardrails, culvert head walls, etc., either on the inside or outside of the curve, and the degree of curvature and tangent width of the pavement. The observations shows that traffic center lines do accomplish the separation of the traffic; and they apparently show that a crowned section, even though superelevated, has the effect of causing the traffic to seek the favorable slope on the inside of the curve. But because of the presence of complicating factors the relation between the degree of curvature and the tangent width of the pavement and the amount of widening required on the curve is not revealed.

Grades.—The distribution of traffic on grades seems to differ only slightly from the distribution on level roads. There is, however, a noticeable departure from the normally preferred course by the traffic moving down hill on light grades. In practically every case observed the traffic under this condition moves slightly toward the center of the road. The explanation advanced is that light down grades do not suggest reduction of speed, but that the drivers do take the precaution of moving slightly away from the edge of the pavement. No such tendency is observed on heavy grades and the presumption is that operators reduce speed on such grades and, at the reduced speed, the instinctive fear of the pavement's edge is lessened.

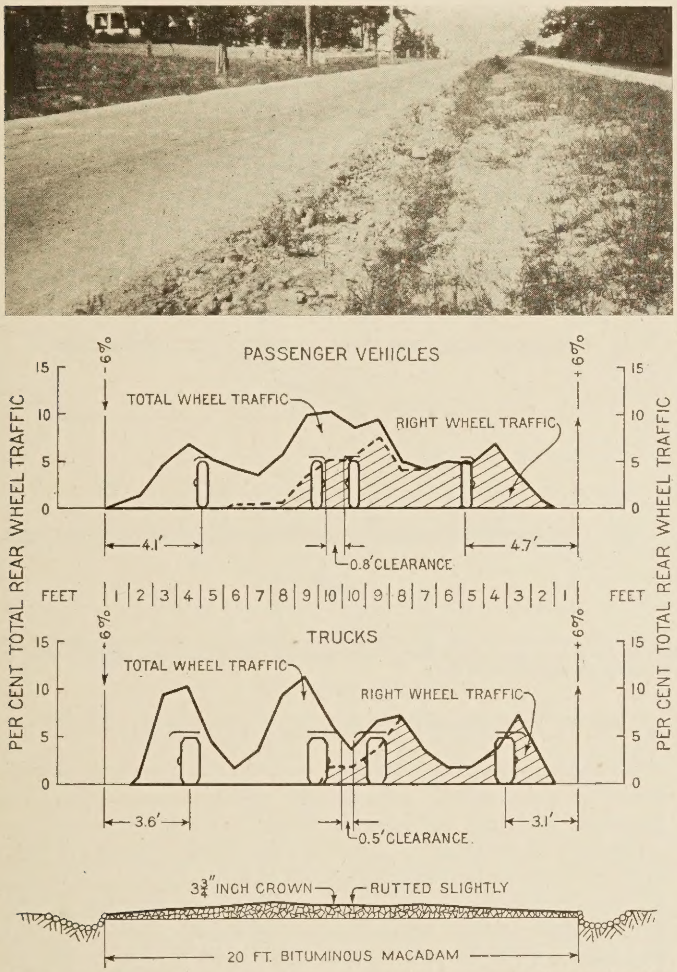


Fig. 2.—Test 10, made on a 20-foot bituminous macadam road with a bad cobble gutter at each side, shows the effect of the concentration of traffic at the center of the surfaced way caused by the condition of the gutter. Increasing concentration at the center may be expected to follow the development of the ruts, leading to still more rapid deterioration of the surface

Other factors affecting lateral distribution.—The observations indicate that other factors, such as the crown of the road, the condition of the shoulders, the presence of concrete shoulders at the sides of a bituminous pavement, center traffic lines, and the presence of roadside structures such as guardrails, culvert headwalls, etc., have a noticeable effect upon the lateral distribution of the traffic. Excessive crown is shown to cause a concentration of traffic at the center of the roadway. A bad shoulder has a similar effect, and guardrails and other similar structures suggesting roadside danger also cause the traffic to move away from the apparent danger and toward the center of the road. Smooth, white concrete shoulders at the edge of a black surface seem to lure the traffic toward the side, and center lines, on tangents as well as on curves, exert a marked separatory influence.

In one case roughness of the surface at a distance from the edge approximately equal to the wheel gauge of passenger vehicles appears to have reduced the used width of the pavement by 1 foot, because of the reluctance of operators to drive with their inner wheels on the rough surface.

Maximum traffic concentrations.—Considering all widths of pavement and all conditions, the maximum percentage of the total traffic concentrating upon a single foot of width is found at the center of a 14-foot pavement for passenger vehicles and at the center of a 15-foot roadway for trucks. The heaviest concentration on a pavement 18 feet wide or wider is shown to be approximately half of these maxima for both classes of vehicles.

On curves and on light grades the point of greatest concentration shifts from the center toward the inside of the curve and the uphill side of the road, respectively. On concrete roads the lines of maximum concentration are clearly marked by the dark stains caused by oil which drops from the center of the drip pans of the vehicles. (See illustration on cover.) The darkest part of these stains which, because of the favorable slope of the drip pans, are always more intense on the uphill side of the road, corresponds to the center of the track of greatest concentration. The heaviest wheel concentration may generally be expected at a distance from the center of the stain equal to one-half the wheel gauge of the vehicles toward the center of the road; and when the distances thus measured reach or slightly pass the center of the road a maximum concentration for the traffic may be expected at the center. Markings, in appearance similar to those caused by drip-pan droppings, may sometimes be observed on concrete roads near points where they abut bituminous surfaces. In such cases, however, the marks are caused by the wheels themselves, and indicate directly the lines of greatest wheel concentration. Similar lines develop on bituminous pavements shortly after the application of a seal coat, caused, in this case, by the earlier ironing down of the surface application at the lines of greatest traffic.

Bearing upon the design of pavements.—One of the most useful results of the observations is the evidence they present with regard to the points of application of the critical motor truck wheel loads. By demonstrating that motor trucks are habitually driven closer to the edge than passenger vehicles, and by showing that the average distance of the rear wheels of the trucks from the edge is little more than 1½ feet on most pavements, the study emphasizes the wisdom of the thickened-edge design, and indicates that the assumption of a point of application of the load at a distance of 6 inches from the edge is conservative.

The study shows convincingly that a census of total traffic may not always describe the full service rendered by a particular highway. In one of the observed cases, for example, 18 per cent of the total number of wheel applications came within a foot of the edge of the pave-

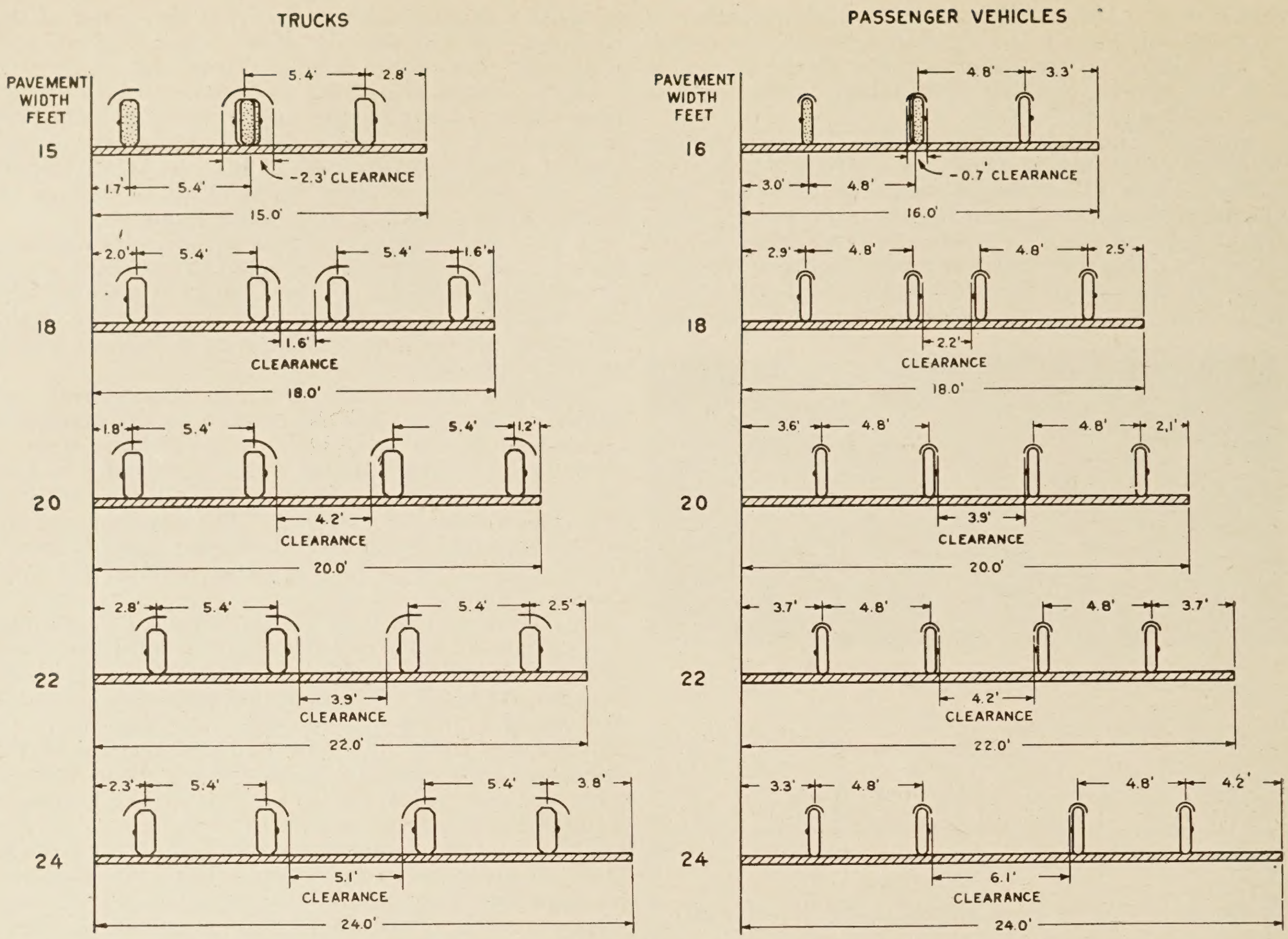


FIG. 3.—Average distribution of traffic on road surfaces of various widths from 15 to 24 feet. Eighteen feet is the minimum width which gives positive clearance for all vehicles in passing at the preferred position. The clearance increases with the width of the pavement, but becomes unnecessarily large when the width exceeds 20 feet. Widths of 22 and 24 feet are apparently excessive for two lines of traffic and not great enough for three lines

ment; in another case only 4 per cent of the total wheel passages were within the first foot. What effect such a difference may have upon the design of the pavement is a matter which will need to be considered carefully in the development of rational methods of road design.

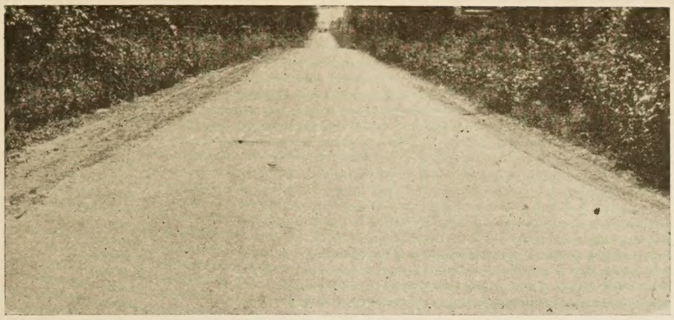
Although the greater concentration of the traffic at one point than at another is likely to cause little difference in the surface wear by attrition, it is possible that a study of the distribution of traffic in connection with surface and subgrade failures may show a more intimate connection than at first glance may appear. One of the roads observed in this investigation may be taken as an example of such a failure. The road, observed in test 10 (Fig. 2), has a 20-foot pavement, but the presence of a bad cobble gutter at each side has forced the traffic to concentrate on the central portion of the pavement, resulting in the formation of ruts which cause a still higher concentration.

Although this paper presents no data relative to the effect of snow upon lateral distribution it may be pertinent to point to the experience of many of our cities during the past winter. The extensive damage revealed when finally the snow blanket of last January was removed—obviously the result, mainly, of the concentration of traffic in snow ruts—should convince the least foresighted of the falsity of that economy which withholds funds for snow removal only to expend greater sums for street repair.

WIDTH OF 18 TO 20 FEET AMPLE FOR TWO-WAY TRAFFIC

Assuming that the proper width of a two-way pavement is that width which will provide safe clearance between passing vehicles without forcing their drivers to reduce the distance between the outer wheel and the edge which is instinctively felt to be safe, it appears from the observations that a width of 18 feet is the minimum which should be adopted for two-way passenger-vehicle traffic and that widths greater than 20 feet are excessive. Trucks require 20 feet for safe passing, but do not fully utilize additional width.

Table 2 presents data on the habits of drivers operating over roads of various widths from 14 to 24 feet, under conditions of fair shoulders, level grades, and on tangents. From this table it appears that passenger-car drivers habitually maintain a distance of from 1½ to 4 feet between the outer wheel and the edge of the pavement, and that truck drivers operate somewhat closer to the edge, but prefer not to approach closer than 1½ feet. These distances, then, define the preferred tracks of the two kinds of vehicles, and may be taken as criteria in deciding upon the adequacy of any given road width. Viewed in this way it appears that pavements less than 18 feet in width are decidedly too narrow, since they provide no clearance for passenger cars or trucks. The 18-foot width is apparently great enough for passenger-car traffic but not quite wide



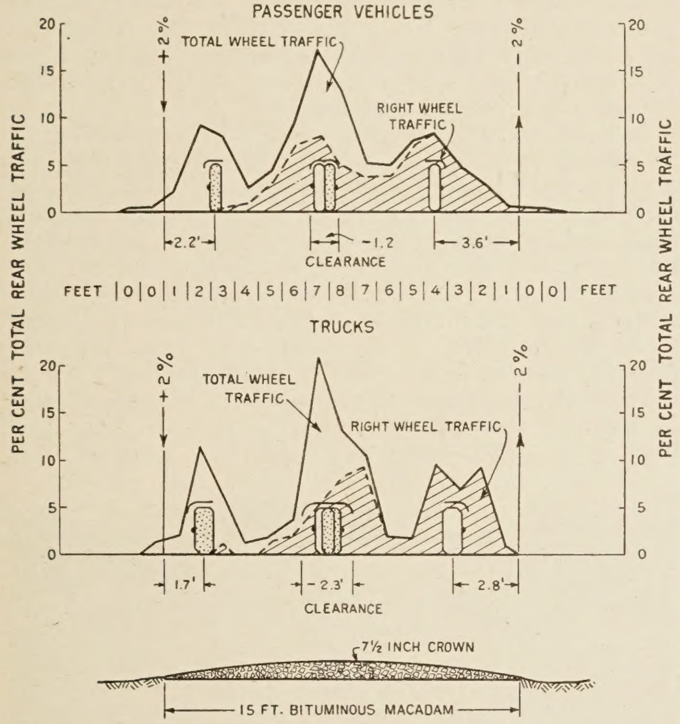


FIG. 4.—Test 7, made on a 15-foot road, shows how the maximum concentration of traffic occurs at the center on roads of such narrow width. The steep crown in this case accentuates the concentration at the center; and the effect of a slight downhill grade is noticeable in the greater distance of the average wheel position from the edge on the downhill side

enough for trucks. The width of 20 feet gives ample clearance for trucks and is apparently not excessive for automobiles. Further increase in width is apparently utilized by the drivers to increase the center clearance, but the added clearance is obviously not greatly needed for safety, for it is shown that the presence of a railroad bridge abutment near the sides of a 24-foot surface (test 12) will cause the truck traffic to give up 2.6 feet of clearance, and a slightly rough surface on a 22-foot road (test 21) reduces the clearance of passenger vehicles by 1.9 feet.

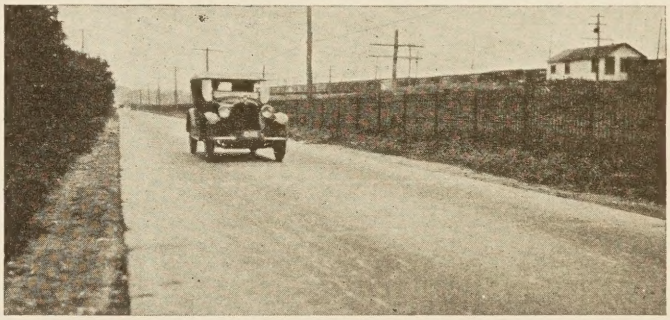
The motor-truck driver, frequently maligned by irate motorists as a road hog, finds unexpected comfort in the graphs which clearly show that he consistently drives closer to the edge of the pavement than his defamers. Before framing a retort, however, it would be well for him to remember that the graphs show him to be a consistent driver rather than a courteous one. The well-developed peaks representing his wheel tracks show that he adheres closely to a fixed path at his chosen distance from the edge, departing from it neither to occupy the center of the road when alone nor to give greater space to another vehicle in passing. The slower speed of his vehicle seems to permit him to drive closer

TABLE 2.—*Average traffic lanes and clearances of motor trucks and passenger vehicles on pavements of various widths. All on tangents with fair shoulders*

Test No.	Pavement type	Width	Average distance of outer wheel from edge		Average clearance
			Left	Right	
	PASSENGER VEHICLES				
		Feet	*Feet*	*Feet*	*Feet*
9	Bituminous macadam	14	1.6	2.2	−0.2
8	do	16	3.0	3.3	−0.7
4	Concrete	18	2.9	2.5	2.2
6	do	20	3.4	3.1	3.1
23	Bituminous macadam	22	3.7	3.7	4.2
21	do	22	4.2	5.1	[1] 2.3
17	Granite block	24	3.3	4.2	6.1
12	Bituminous macadam	24	4.4	4.2	[2] 5.0
	MOTOR TRUCKS				
7	Bituminous macadam	15	1.7	2.8	−2.3
4	Concrete	18	2.0	1.6	1.6
6	do	20	2.7	2.4	2.1
23	Bituminous macadam	22	2.8	2.5	3.9
21	do	22	1.7	2.6	[1] 4.9
17	Granite block	24	2.3	3.8	5.1
12	Bituminous macadam	24	4.0	4.7	[2] 2.5

[1] This road has 2½-foot concrete shoulders on each side, which normally would tend to increase the clearance. The presence of a rough place in the pavement about 6 feet from each edge causes passenger vehicles to forego the smooth concrete edge, because to do so would place their inner wheels on the rough place. Motor trucks are not affected, because their broader gauge permits them to use the concrete shoulder without running with their inner wheels on the rough place

[2] Railroad bridge abutments at each side of pavement cause reduction of clearance



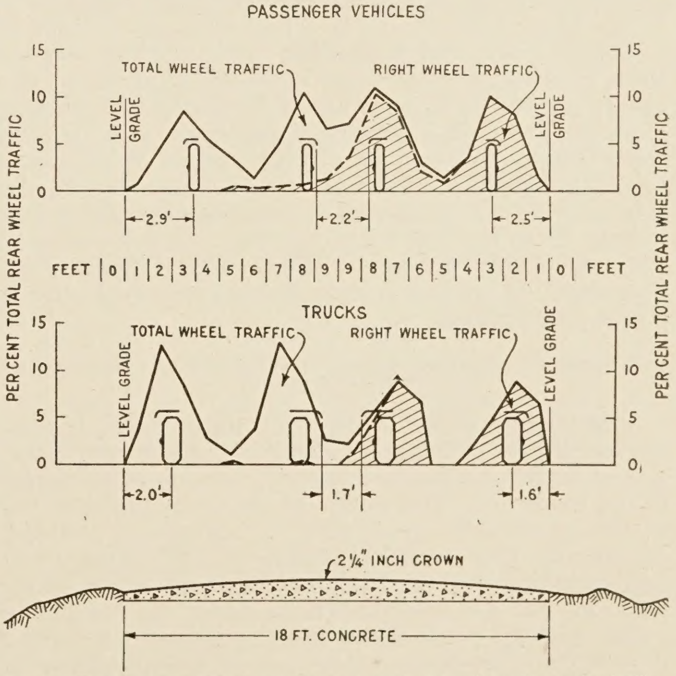


FIG. 5.—Test 4, on an 18-foot concrete pavement, shows how the center traffic concentration which characterizes the narrow roads is relieved by widening. The good shoulders on this road encourage traffic to use the surface to the very edge. Contrast this condition with that shown in Figures 15 and 16 where a bad shoulder condition clearly discourages the use of the edges of the surface

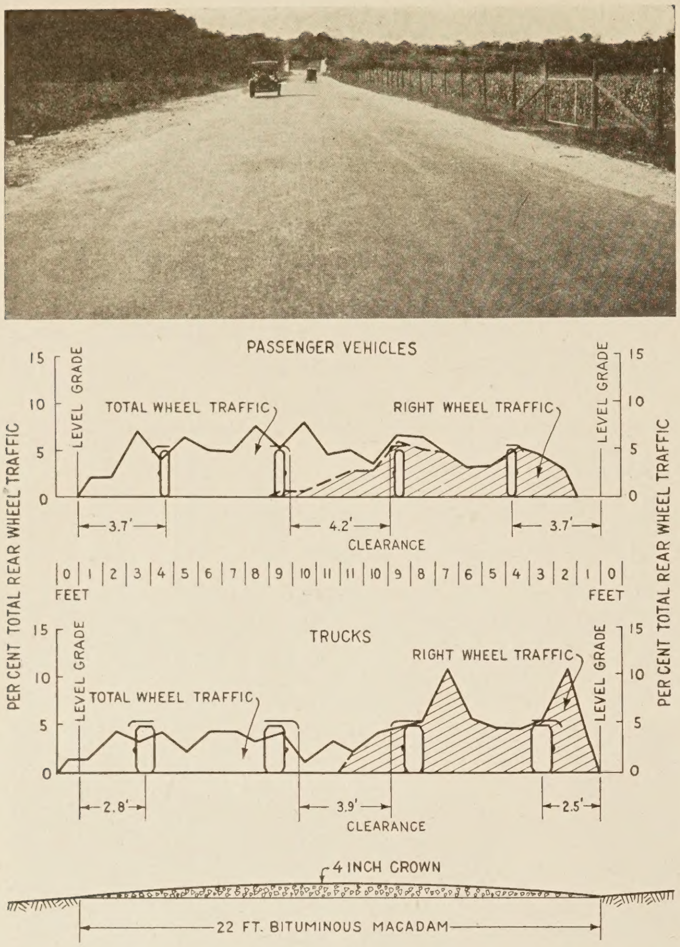


FIG. 6.—Test 23, made on a 22-foot bituminous macadam road, shows how the peaks of traffic concentration are reduced by widening the surface beyond 18 feet. The maximum percentage of passenger vehicle and truck concentration at one point are 8.1 and 11.1 respectively. The peaks are still further reduced by widening to 24 feet (see Fig. 7)

to the edge with a sense of safety than the drivers of passenger cars; and he prefers this position because there it is not necessary, as it would be closer to the center, to pull aside continually to permit the passing of faster cars. The drivers of passenger cars, on the other hand, possessed of a more mobile vehicle, apparently shuttle back and forth from the center to the side of the road, occupying the center when alone and pulling off to the side when passing. This is probably the reason why the peaks of passenger-vehicle wheel concentration are not so pronounced as the peaks in the motor-truck graphs.

THE POINT OF GREATEST TRAFFIC CONCENTRATION AFFECTED BY WIDTH OF ROAD

When width alone is the controlling factor, it may apparently be anticipated that the greatest concentration of traffic on a narrow road will come upon the center of the roadway. This is due to the overlapping of the wheels of vehicles proceeding in opposite directions. Apparently this condition obtains for all widths up to and including 18 feet. Beyond that width the center peak of the distribution graph tends to become a valley and the peak of maximum wheel concentration is split into four lesser peaks, two of which appear on each side of the road.

Thus, in test 7 (Fig. 4) made on a 15-foot road the maximum percentage of the traffic concentrated on a single foot of width is 20.7 for truck traffic and 17.4 per cent for passenger-car traffic, each at the center of the road. The effect of widening the surface to 18 feet is shown by test 4 (Fig. 5) made on a level section of concrete road, which to all appearances is normal in every respect. The observations on this road show that both the passenger vehicle and truck traffic concentrate in four pronounced peaks, two on each side of the road, the maximum in the case of passenger vehicles representing 10.9 per cent of the total traffic, and in the case of trucks 12.7 per cent. What happens on a 24-foot road is illustrated by test 17 (Fig. 7), made on a granite-block pavement, where it is found that the peaks representing the left and right side concentrations are more widely separated and reduced to 7 per cent and 10.2 per cent, respectively, of the total traffic for passenger vehicles and trucks.

It thus appears that the width of the pavement is an essential consideration in interpreting the effect of a given total traffic on the pavement. Although the experiments of the Bureau of Public Roads indicate that surface wear of modern pavements by rubber-tired vehicles is practically negligible, the relative concentration of the traffic at various points on the surface, and the direction of the traffic may be found to be instrumental in the causing of other types of failures, such as fatigue and subgrade failures. If, as is generally suspected, the causation of corrugations in bituminous surfaces is related to the direction and volume of traffic using the road, it is possible that

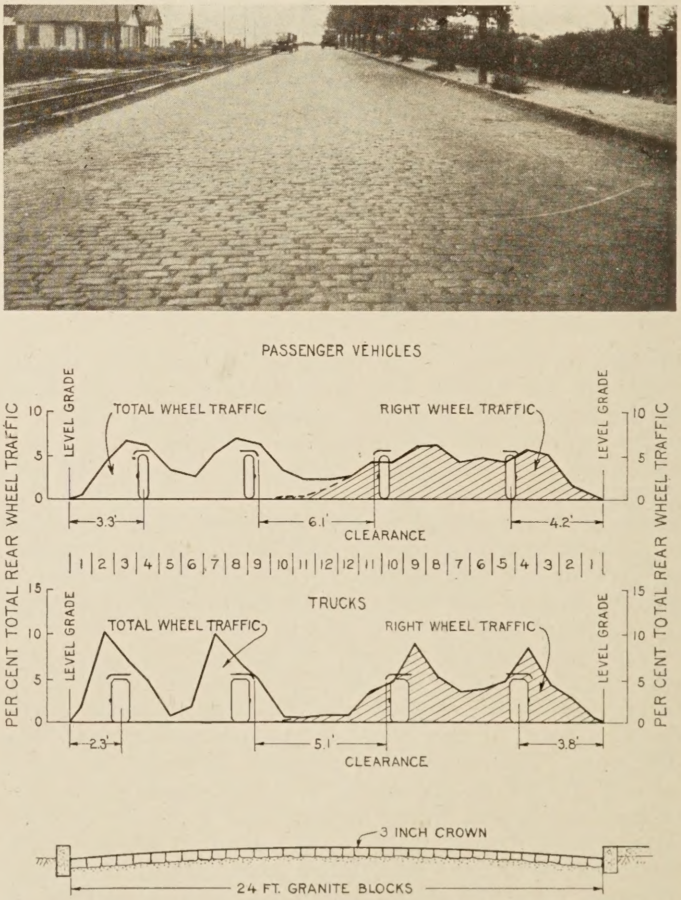


FIG. 7.—Test 17, made on a 24-foot granite block pavement, shows the effect of widening the pavement on the concentration of traffic. The maximum peaks in this case are 7 and 10.2 per cent of the total traffic for passenger vehicles and trucks respectively. Shade trees at the right apparently cause the traffic to keep at a greater distance from the right-hand curb

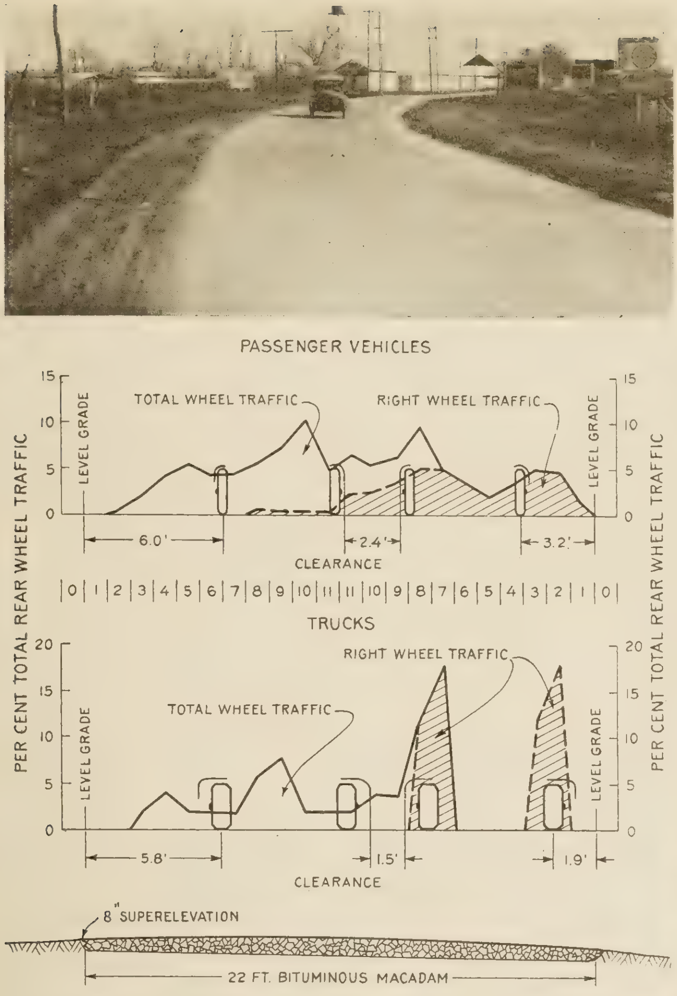


FIG. 8.—Test 18 shows the distribution of traffic on 22-foot bituminous macadam road at an 11° 30′ curve which has a crowned superelevated section. Vehicles traveling on the outside of the curve crowd toward the inside to take advantage of the favorable slope and reduce curvature, and in the absence of a center line there is nothing to counteract this tendency

certain commonly observed characteristics of such waves or corrugations may be explained by observations of lateral distribution. It is shown by the present tests that the center of the road almost always carries a traffic in which vehicles moving in opposite directions have their wheel tracks superimposed one upon the other; and it is possible that the disappearance of the waves at the center, which has been often observed, is due to the passage of approximately the same number of wheels in each direction, thus neutralizing the effect of direction of traffic.

THE EFFECT OF CURVATURE ON LATERAL DISTRIBUTION

Six of the points of observation were on horizontal curves. Two were on 24-foot bituminous macadam roads (tests 16 and 19), one with an 18 and the other with a 20 degree curve. Each had a white center line and both were superelevated, the 18-degree curve 9 inches with a crowned section and the 20-degree curve 6 inches with a plane section. The one 22-foot road (test 18) was also surfaced with bituminous macadam, and its 11-degree-30-minute curve was superelevated 8 inches with a crowned section which practically neutralized the effect of the superelevation in the outer quarter. This road had no center line and no other feature of any kind which might conceivably guide the traffic. Two 20-foot roads with curvature of 8 and 15 degrees (tests 13 and 14) introduced another element. Both were superelevated 5 inches with crowned sections and, as in the case of the 22-foot road, the crown neutralized the superelevation in the outer quarter. But both of these roads had 2½-foot concrete shoulders at each side of the 15-foot bituminous-macadam center section. Finally, test 22 was made on an 18-foot concrete road with curvature of 25 degrees, the sharpest of all the curves observed. The plane section had a superelevation of 5 inches and there was no center line; and the element which distinguished this curve from all the others, in addition to its heavy curvature, was a 5-foot fill at the outside of the curve, protected by a guardrail within 2 feet of the edge of the pavement.

In these six curves, then, we would expect to find intermingled the effects of each of the various elements; and unless the facts are kept clearly in mind, it will seem that there is no rational explanation of the striking differences which appear in the graphs. It is best to approach the detailed study by considering first the 22-foot, 11-degree-30-minute curve (Fig. 8). It is the simplest of the six. It has no center line; its shoulders on both sides are good; and there is a full view ahead from one end of the curve to the other. There are only two apparent reasons why the

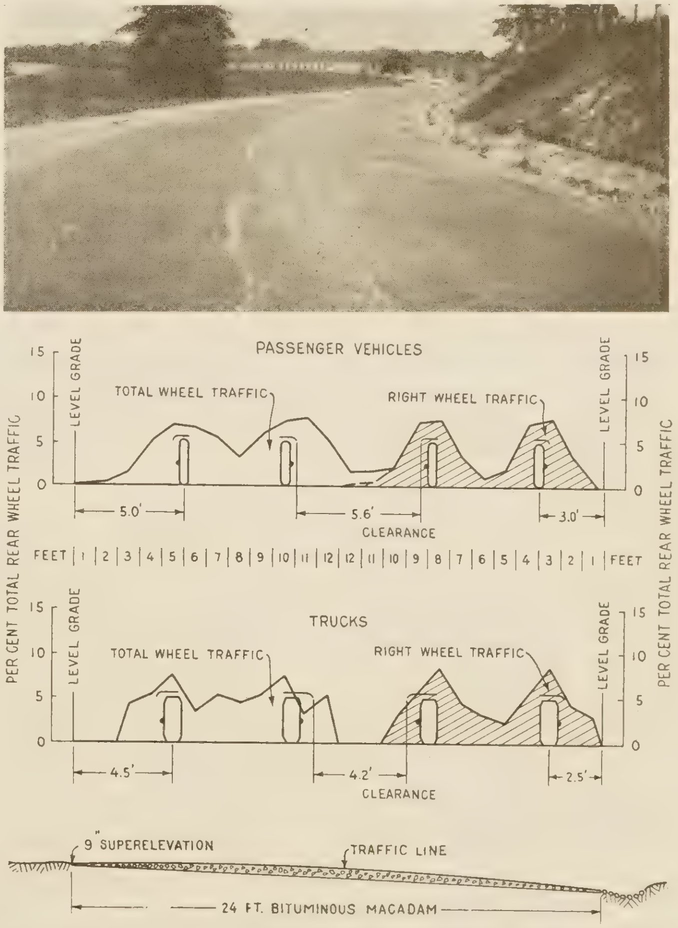


FIG. 9.—Test 16 was made on a 24-foot bituminous macadam road at an 18° curve. The curve is superelevated 9 inches with a crowned section and vehicles traveling on the outside move over to take advantage of the favorable slope, but are prevented from overlapping the center by the guiding line. The bank at the right causes the inside traffic to keep well out from the inner edge

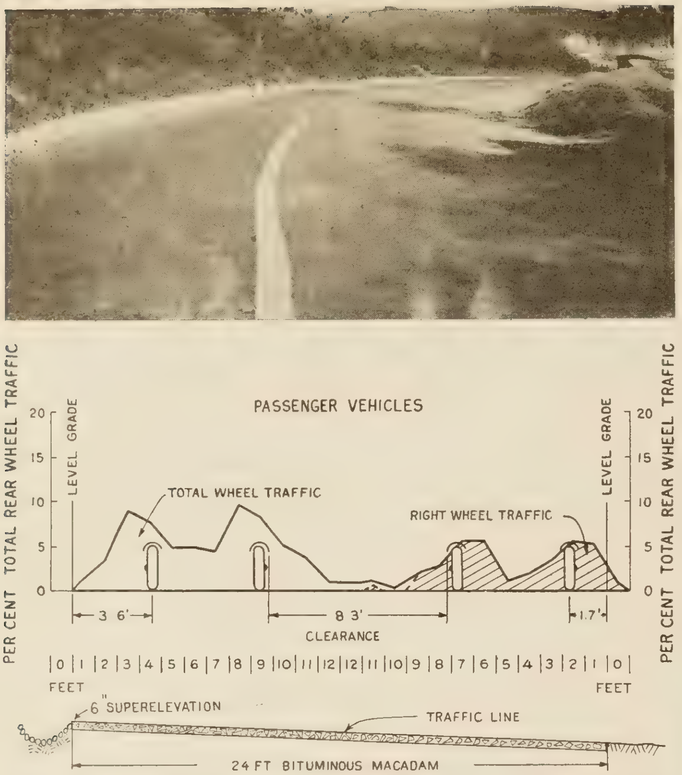


Fig. 10.—Test 19, made on a 24-foot bituminous macadam road at a 20° curve with a plane superelevated section and center line, shows a better separation of the traffic than test 16 (Fig. 9) made on a similar road with crowned superelevated section

traffic on this curve should shift from its preferred position on the tangent. These are the instinctive desire to cut across the curve and thereby lengthen the radius of the curved course; and the fact that the crowned section neutralizes the superelevation of the outer quarter of the road. If, therefore, the vehicles traveling on the outside of the curve are to get any benefit from the superelevation, their course must be shifted toward the inside of the curve so as to place them on the favorable tilt. This is apparently exactly what happens. The high point of the cross section if approximately 6 feet from the outer edge; and at this exact point we find the center of gravity of the outer wheel diagram, indicating that the average driving position of the vehicles—both trucks and passenger cars—is the position nearest to the outer edge at which the vehicle can be driven with full advantage of the superelevation. In taking this position the average position of the inner wheels of the outer traffic is brought practically to the center of the road in the case of passenger vehicles and slightly beyond it in the case of trucks. A very considerable percentage of the passenger-car traffic moves with the inner wheel more than 3 feet beyond the center, and the truck traffic crowds over nearly as far.

With this test in mind, let us now turn to the two 24-foot roads (Figs. 9 and 10). These two curves have practically identical conditions with one exception. The 18-degree curve has a crowned section and the 20-degree curve a plane section. Both are surfaced with bituminous macadam; both have center lines. The shoulder conditions differ slightly, in that one has a cobbled gutter at the inside of the curve and the other at the outside; but the gutters are shallow and the pavements are wide, and it does not seem likely, therefore, that this difference can have a material bearing on the behavior of the traffic. The major points of difference between the two curves are the type of superelevated section and the condition of the roadside at the inside of the curve. On the 18-degree curve the bank at the inside of the curve is high enough to obscure the view around the curve; on the 20-degree curve the forward view is not obstructed.

Both of the curves show clearly the separating influence of the center line. The advantage of the plane superelevated section is also indicated by the lesser distance from the outside edge of the pavement to the wheels of the vehicles on the 20-degree curve which is thus treated. On the 18-degree curve the average position of the rear wheels of the outer automobile traffic is found at 5 feet from the edge as compared with 3.6 feet on the sharper curve. On the 18-degree curve, also, the inside traffic operates at a greater distance from the inner edge; but this is undoubtedly due to the obscured vision.

However, the striking fact observable in the graphs of these two tests is the clear separation of the traffic on the left and right sides of the roads, which is doubtless attributable to the center lines. The overrun to the wrong side of the road which is the outstanding

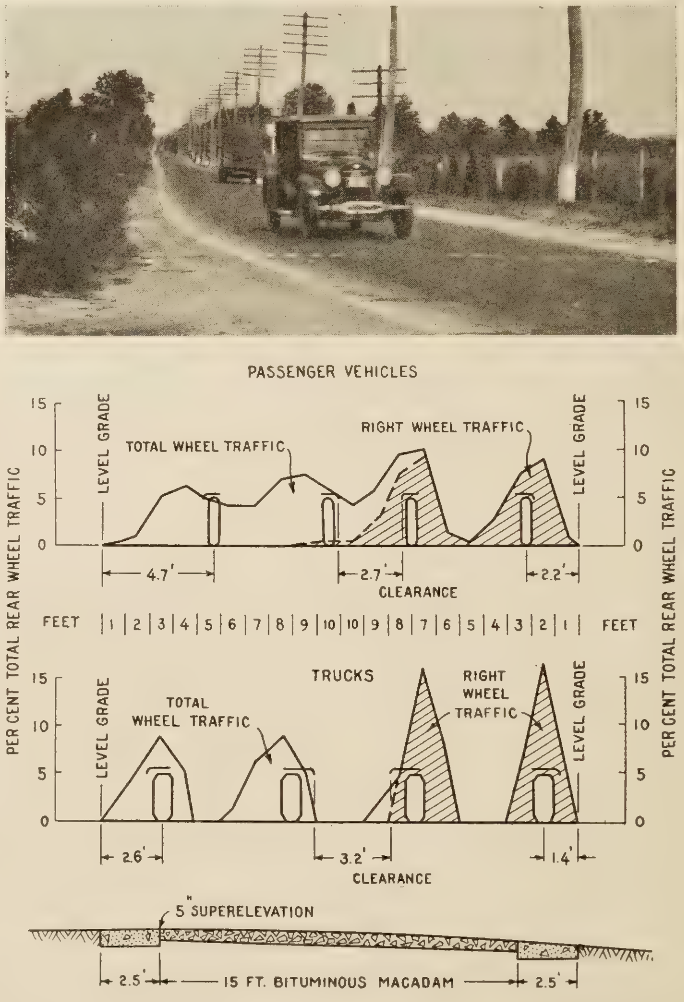


Fig. 11.—Test 13 shows the traffic-separating effect of concrete shoulders on curves. This effect is offset in a measure by the crowned superelevated section The curvature is 15°

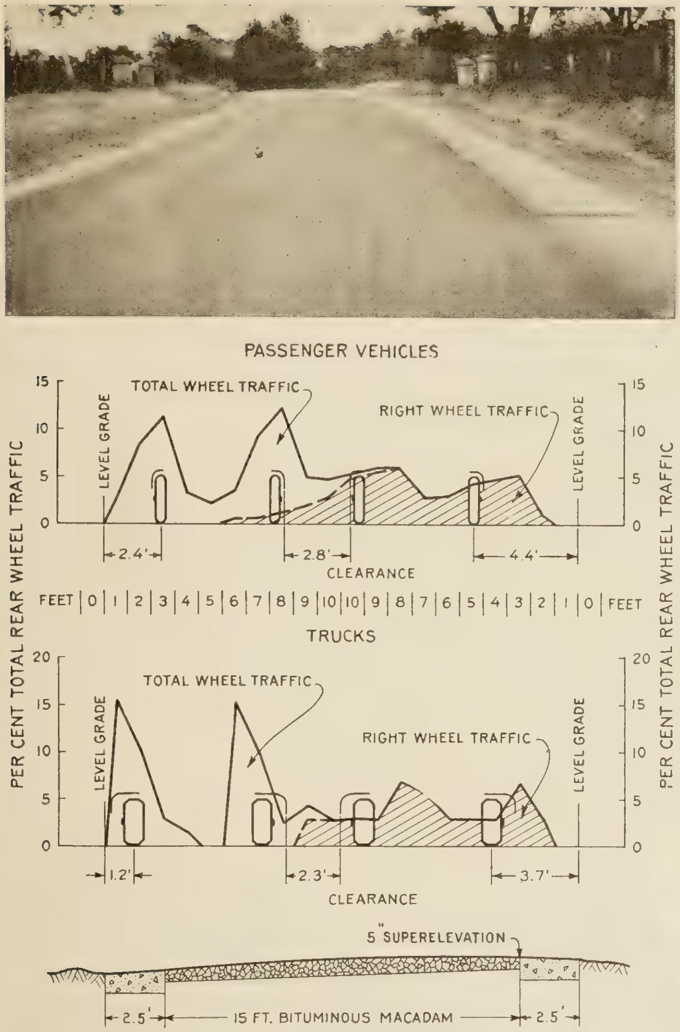


Fig. 12.—Test 14, like test 13 (Fig. 11), shows the contrary influences of concrete shoulders and a crowned superelevated section on the distribution of traffic on an 8° curve

characteristic of the graphs of the 22-foot road is almost completely absent in the graphs of these 24-foot curves; and the significance of the difference is heightened by the fact that the latter are almost twice as sharp as the former.

Obviously, therefore, in the comparison of the observations on these three roads there is strong argument for the plane superelevated section and a convincing demonstration of the effectiveness of the center line.

In the two 20-foot pavements (Figs. 11 and 12) we have an opportunity to observe a conflict between the contrary effects of a guiding line and a crowned superelevated section. The guiding line in these pavements is not a center line but an attractive white strip at the sides of their black surfaces. Obviously it is effective to a degree, for, on these pavements the outside traffic does not crowd toward the inside until it has both wheels on the favorable slope of the crown; but it is equally clear that the inner slope is attractive to a considerable percentage of the outside vehicles, especially the automobiles, some of which crowd over 4 or 5 feet beyond the center of the road.

Finally we come to the 18-foot curve (Fig. 13) which is different from all the others in these respects: It is paved with concrete throughout, it is much the sharpest,

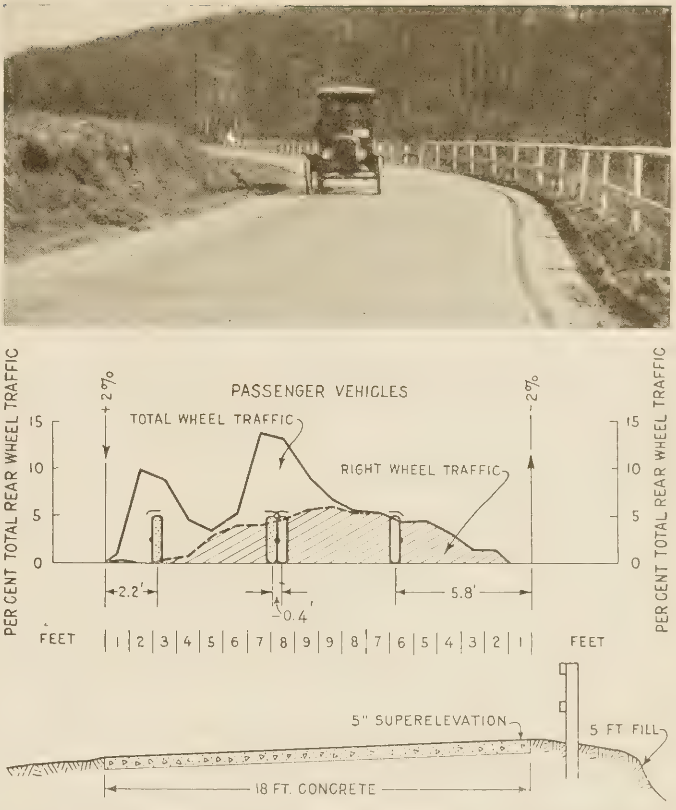


Fig. 13.—Test 22, made on an 18-foot concrete pavement at a 25° curve with plane superelevated section and no center line, shows the effect of the absence of the center line and the presence of a menacing fill at the outside of the curve on the distribution of traffic. The shift toward the inside of the curve is accentuated by the slight downhill grade at the outside

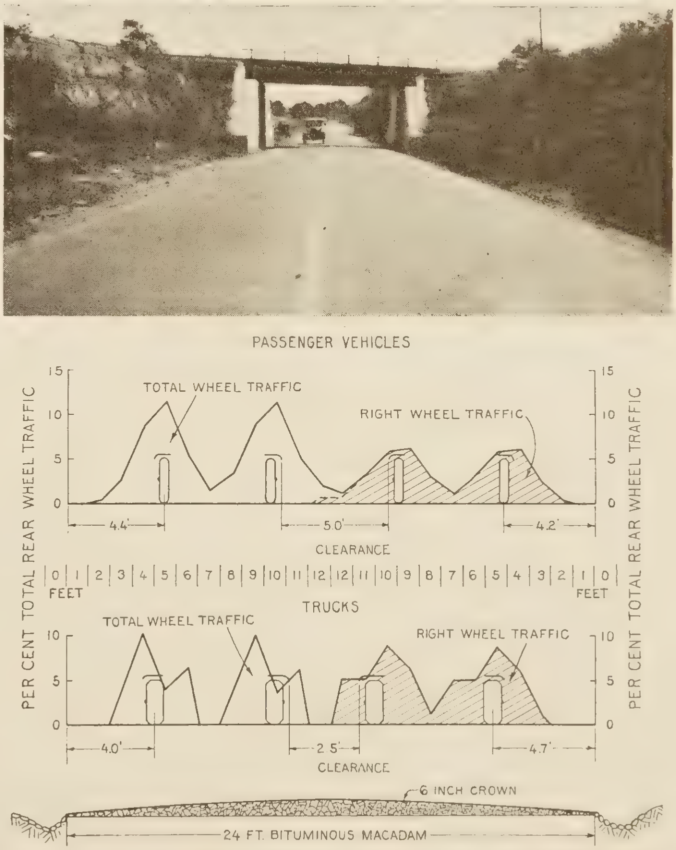


Fig. 14.—Test 12. The bridge abutments apparently reduce the effective width of this 24-foot bituminous macadam road to 20 feet, but the center line effectively separates the traffic

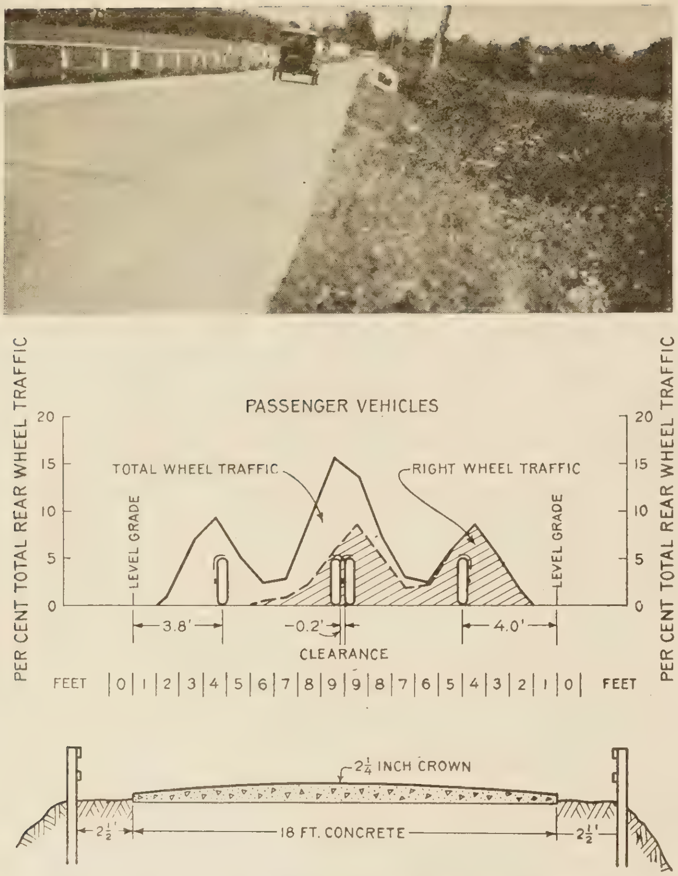


Fig. 15.—Test 3, made on an 18-foot concrete road, shows that the effective width is reduced to 16 feet by the low, narrow shoulder and menacing fill and guard rail

and it has at its outside a menacing fill which is guarded by a wooden fence that stands within 2 feet of the edge of the pavement. It is similar to one of the 24-foot pavements in having a plane superelevated section; it is similar to the 22-foot pavement in having no center line or other guiding element. The deviation of the automobile traffic from the proper legal course is more marked on this curve than on any of the others. Some of the outer traffic actually reaches the inner edge; the average position of the outer rear wheel is almost two-thirds of the distance from the outside to the center; and there is practically no clearance between the two lines of traffic. What is the explanation of these conditions? Undoubtedly the high degree of curvature is responsible in a large measure; for while the shift of course gains nothing in point of superelevation, there is an appreciable advantage to be gained on such a sharp curve in the way of increased radius of curvature. Moreover, the presence of the fill and guardrail at the outside of the curve, and the fact that the outside traffic is moving down grade, undoubtedly causes a movement away from the apparent danger. Add to these facts the further fact that there is no warning or separating line or other device to counteract the tendencies set up by the other factors, and we have a fairly satisfactory explanation of the behavior of the traffic on this road.

The observations are not numerous enough to reveal the general relation which probably exists between the degree of curvature, the tangent width of the pavement and the amount of widening on the curves which would

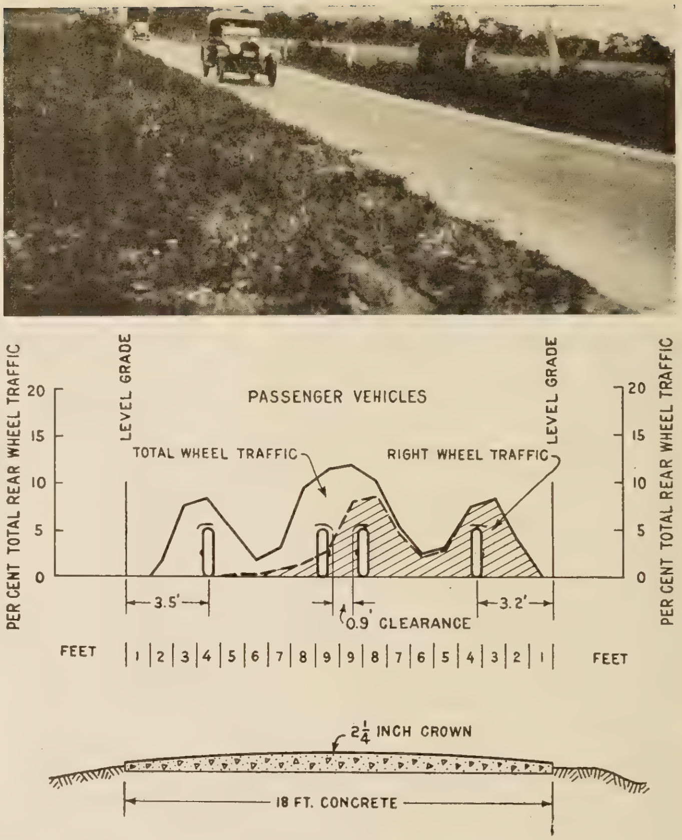


Fig. 16.—Test 1, also on an 18-foot concrete road, shows the loss of effective width caused by the low shoulders. Compare with roads of the same width but good shoulders shown in Figures 5, 17, and 18

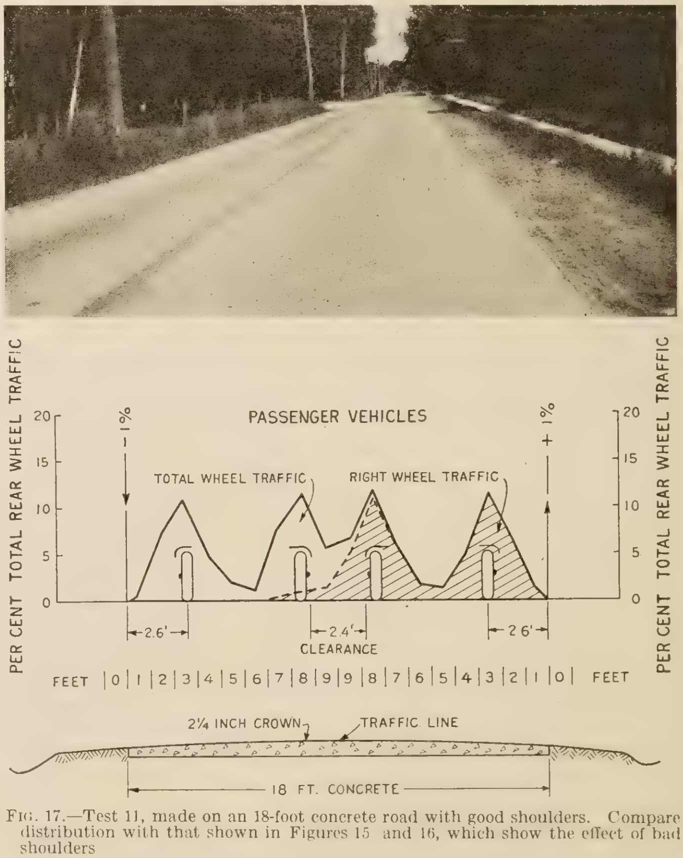


Fig. 17.—Test 11, made on an 18-foot concrete road with good shoulders. Compare distribution with that shown in Figures 15 and 16, which show the effect of bad shoulders

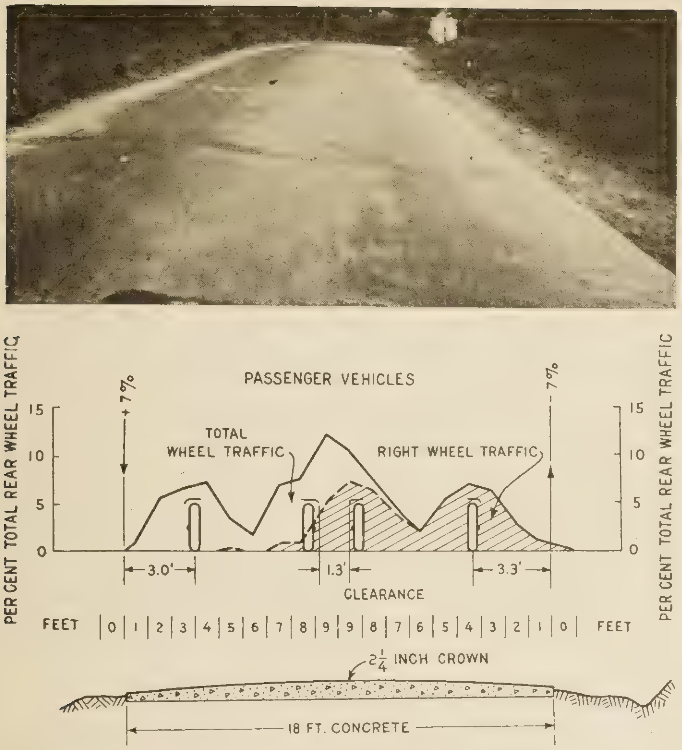


Fig. 18.—Test 20, also on an 18-foot concrete road, shows that the good shoulders permit full use of the surface, but the curve to the right just beyond the point of observation and the obstruction of the view of the right-hand traffic both cause a movement of the traffic toward the center, resulting in a center peak of traffic concentration. The presence of a center line would probably counteract this tendency

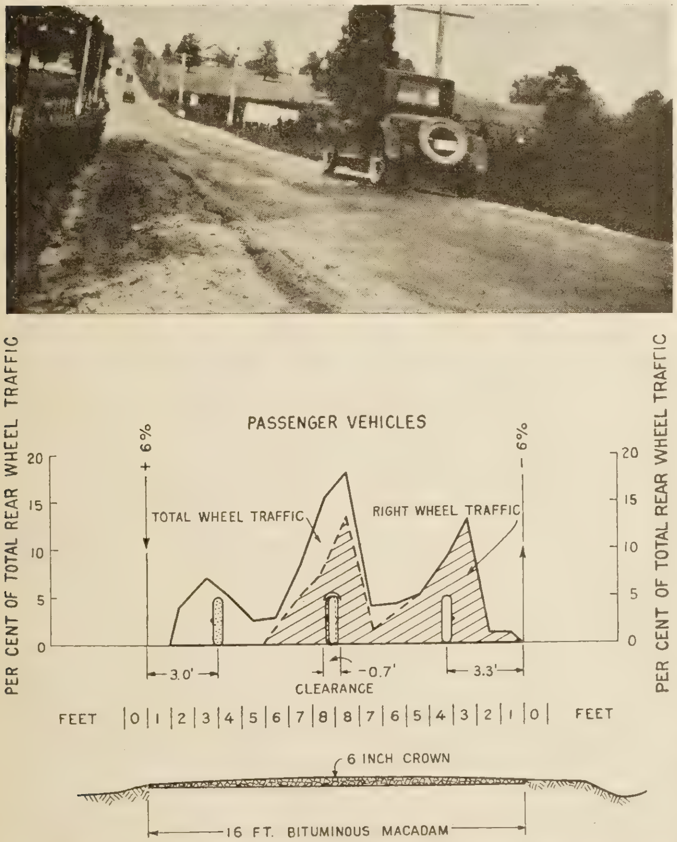


Fig. 19.—Test 8, a 16-foot bituminous macadam road, is effectively only 15 feet wide on account of the ragged edge at the left. The steep crown accentuates the tendency to crowd toward the center

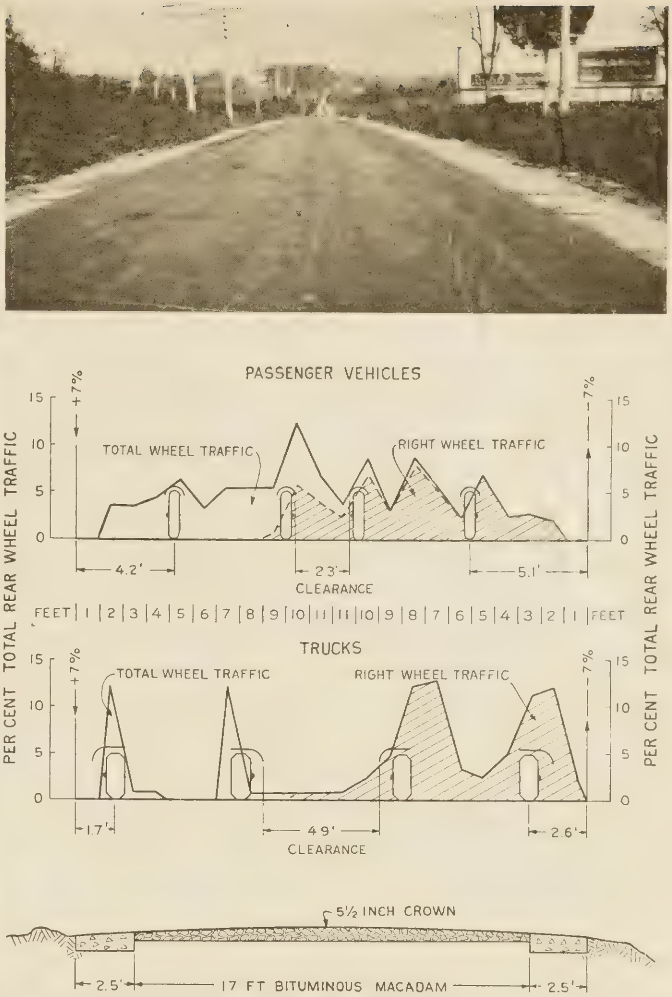


Fig. 20.—Test 21 shows how the effective width of a pavement may be reduced by defective surface some distance from the edge. To avoid the roughness of the surface approximately 6 feet from each edge the passenger vehicles keep their inner wheels nearer to the center and thus fail to utilize the full width of the road. The wider gauge of the trucks permits them to "straddle" the rough surface and still travel with their outer wheels at the edge

provide clearance equal to that provided on the tangent. The tests do indicate that the presence or absence of a center line, the character of the superelevated section and the roadside conditions are factors which should be considered as well as the degree of curvature and the tangent width in estimating the amount of widening required.

TRAFFIC MOVES TOWARD CENTER ON LIGHT DOWN GRADES

The only tendency clearly recognizable in connection with the distribution of the traffic on grades is a slight movement toward the center of the road on the downhill side of light grades. The tendency is not observed on heavy grades, but is apparent in practically every instance on grades of 1 or 2 per cent. The explanation which has been advanced to account for this phenomenon and which seems plausible, is that the vehicles are driven on light grades at practically the same speed as on the level, but that the drivers, sensing, the slightly increased danger, take the precaution of moving away from the edge. On heavy grades the drivers almost invariably reduce speed, and at the lower speed the instinctive fear of the edge is lessened.

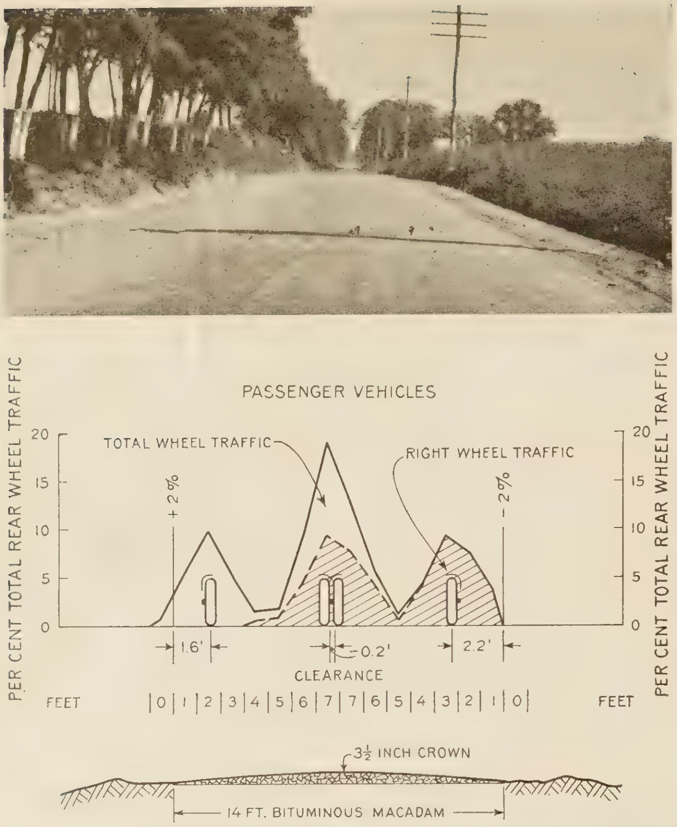


Fig. 21.—Test 9 shows the distribution of traffic on a 14-foot bituminous macadam road. Note that the traffic spreads out onto the shoulder at the left. This fact and the lower crown makes the negative clearance on this road less than that of the 15-foot road shown in Figure 4

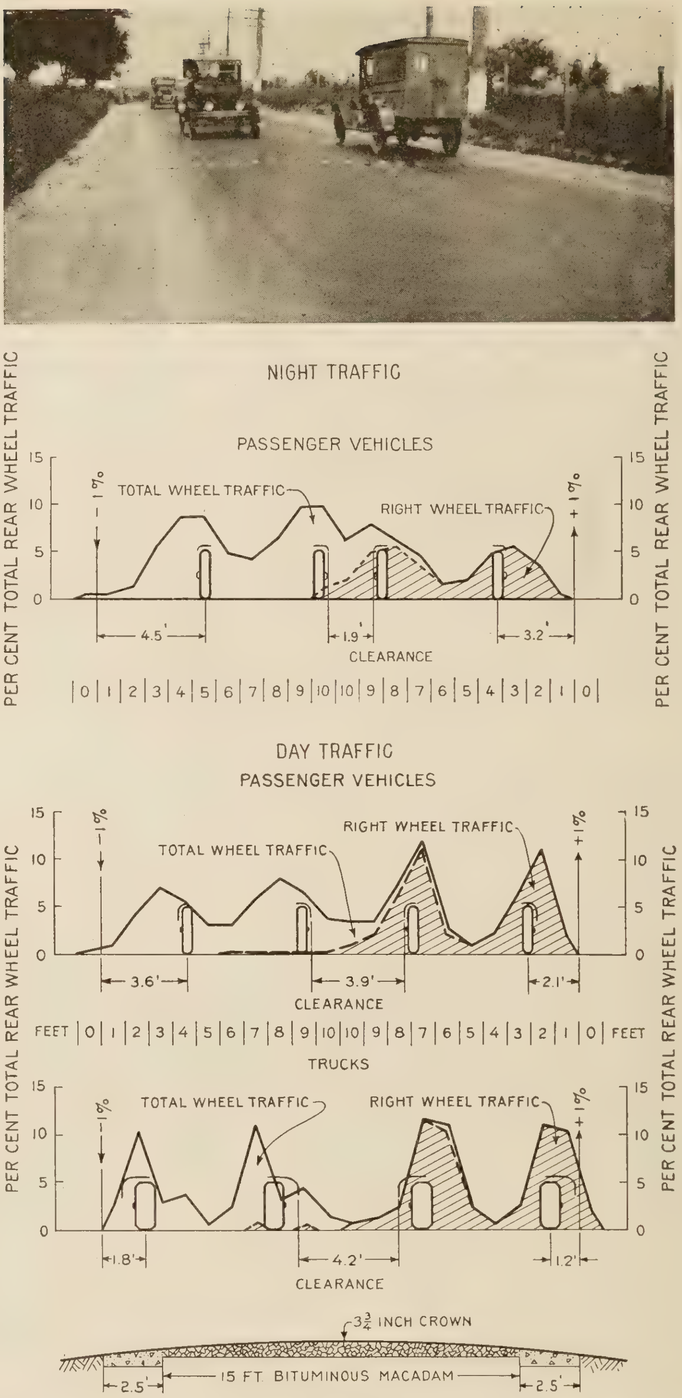


Fig. 22.—Test 5 shows the separating effect of concrete shoulders on tangents and difference in the distribution of traffic at night. Compare with the concrete road of the same width shown in Figure 23 which has a center line for the separation of the traffic

OTHER FACTORS AFFECTING LATERAL DISTRIBUTION

Among the most interesting results of the investigation is the evidence it supplies with regard to the effect of the condition of the roadside and the pavement itself on the distribution of the traffic and the effective width of the pavement. Reference has already been made to the effect of the bank at the inside of the curve observed in test 16. (Fig. 9.) By obstructing the forward view of drivers on the inside of the curve this bank has been shown to cause the inside traffic to move further in toward the center of the road than the traffic on the similar curve observed in test 19. (Fig. 10.) On the other hand, a 5-foot fill at the outside of the sharp curve observed in test 22 (Fig. 13) has been shown to accentuate the tendency of the traffic to move toward the inside of the curve.

It is clear from the graphs that similar roadside conditions have had a like effect upon the distribution of the traffic on tangents, an effect in some cases so pronounced that the effective width of the pavement is reduced from 2 to 4 feet. The effect is not merely to reduce the usage of the pavement near the edges, but, apparently, to positively discourage all use of the pavement near the edges.

In test 12 (Fig. 14), for example, the heavy concrete abutments of an overhead railroad bridge erected at the edge of a 24-foot pavement, with only a narrow cobble gutter between, are shown to so reduce the usage of the outer 2 feet of the pavement at each side as practically to convert it at this point into a 20-foot pavement.

Test 3 (Fig. 15), made on an 18-foot concrete road, shows that the effective width of the pavement is reduced to 16 feet by the presence of a low, narrow shoulder and menacing fill and a guardrail only 2½ feet from the edge of the pavement. Almost as much effect is attributable to the low shoulder observed in test 1 (Fig. 16), also on an 18-foot concrete road. Comparing the observations on these two roads with those on the concrete roads of the same width treated in tests 4, 11, and 20 (Figs. 5, 17, and 18) brings out clearly the fact that it is the roadside condition which has caused the reduction in effective width in these cases. Figures 17 and 18 representing like conditions of character and width of surface and shoulder illus-

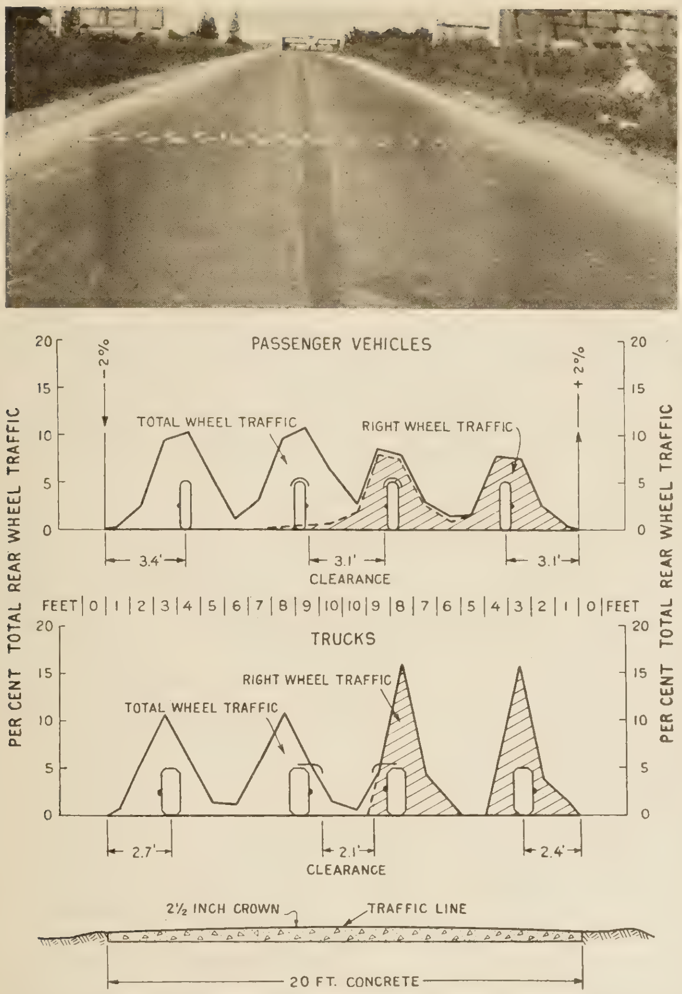


Fig. 23.—Test 6, made on a 20-foot concrete road with center line, shows the separating effect of the black line. Compare with Figure 22 which illustrates the effect of concrete shoulders. Also note how the center of the oil marks coincides with the center of the average position of the vehicles

trate the effect of a center line on the position of the traffic on tangents.

In test 8 (Fig. 19) the road observed has a bituminous macadam surface 16 feet wide which is reduced to an effective width of 15 feet by the ragged edge of the surface on the left-hand side; and a similar result follows from a different surface defect in the pavement observed in test 21 (Fig. 20). Here the defective surface is not at the edge but approximately 6 feet from it on each side. Along a line at about that distance from the edge the surface is so rough as to discourage its use by the traffic. The edges of the pavement are surfaced with concrete and are smoother than any part of the central bituminous macadam section, but because of the specially rough condition 6 feet from the edge it appears that the drivers of passenger vehicles will not travel with their inner wheels at this point, with the result that the outer foot of the concrete shoulder on each side is not used. The wider wheel gauge of the trucks permits them to drive with their outer wheels on the concrete near the edge without placing the inner wheels on the rough surface, and the graph shows that they do utilize the concrete shoulder.

EXCESSIVE CROWN CONCENTRATES TRAFFIC AT CENTER

The effect of excessive crown is indicated by comparison of tests 7 and 9 (Figs. 4 and 21). Test 7 was made on a 15-foot bituminous macadam surface with a crown of 1 inch per foot. Test 9 was made on a similar surface, 14 feet wide with a crown of one-half inch per foot. It is apparent that the greater crown of the wider road has so concentrated the traffic at the center as to reduce the clearance to a negative distance of 1.2 feet as compared to a negative 0.2 foot on the narrower road.

The effect of darkness on the distribution of traffic is illustrated by test 5 (Fig. 22). Observations were made on this road during the night as well as in daylight. It was anticipated that the white concrete shoulders, being more visible at night than the black center section would have the effect of holding the traffic to the edges of the pavement. Comparison of the graphs of day and night observations, however, shows that this result is not obtained to any marked degree. It will be noted that the density of the traffic at the center, which appears as a valley in the graph of the daylight observations, forms a peak in the graph of the night observations. No observations were made on other pavements at night and it is therefore impossible to say definitely that the concrete shoulders have not been effective in some degree. It is possible that on an all-black surface the center concentration might have been found to be even greater.

The comparative effects of concrete shoulders and a center line in separating traffic on tangents are illustrated by comparing with test 5, the results of test 6 (Fig. 23) made on an all-concrete pavement, also 20 feet wide. In relation to the motor-truck traffic especially the concrete shoulders apparently exert a greater influence than the center line.

H. F. JANDA APPOINTED ASSISTANT DIRECTOR OF HIGHWAY RESEARCH BOARD

Announcement is made by Charles M. Upham, director of the highway research board of the National Research Council, of the appointment of H. F. Janda as assistant director. Mr. Janda is especially fitted for this position. He is a graduate of the University of Wisconsin and for two years was assistant city engineer at Portage, Wis. Mr. Janda has not only had a variety of practical experience in engineering but has also acted as instructor and assistant professor of civil engineering at the University of Cincinnati for five years. As associate professor of highway engineering at the University of North Carolina for three years he was in charge of experimental research in cooperation with the State highway commission. Mr. Janda has carried on many important research projects, including studies of capillary moisture in highway subgrades, earth-pressure tests on culvert pipe, and other problems affecting highway construction.

Mr. Janda is located in the offices of the highway research board in the building of the National Academy of Sciences and National Research Council at B and Twenty-first Streets, Washington, D. C.

THE EFFECT OF MOISTURE ON CONCRETE[1]

By W. K. Hatt, Professor of Civil Engineering, Purdue University

THIS paper reports investigations conducted by the Engineering Experiment Station of Purdue University in cooperation with the United States Bureau of Public Roads,[2] the primary purpose of which was to measure the maximum warping and surface deformation of a concrete road slab resulting from nonuniform distribution of moisture, as a basis for estimating possible initial stresses. The tests also yield data of expansion and contraction of concrete, useful in the design of concrete structures.

The investigations were divided into two sections, namely: (1) Observations on a concrete road slab, 7 inches thick, 18 feet wide, and 25 feet long, resting on a porous subgrade, and covered with a tent and housed in a shed to control the distribution of moisture and the effects of temperature; (2) tests of strength and length changes of small beams, some partly and some uniformly saturated.

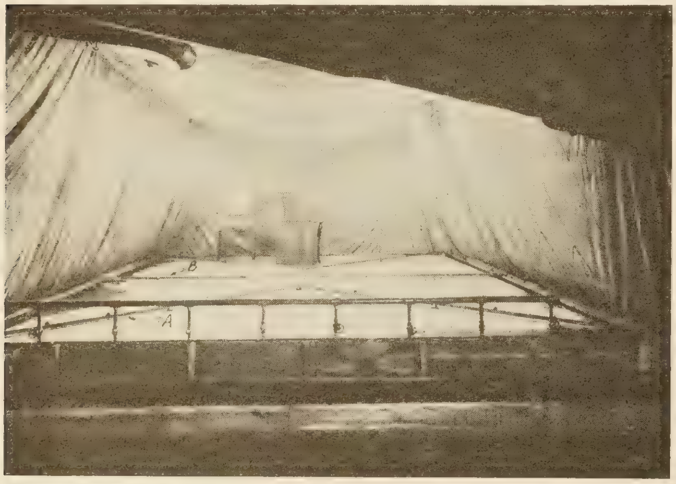


Fig. 1.—General view of concrete test slab showing tent covering and means of saturating subgrade

The following phenomena were examined:[3]

1. The maximum distortion (including deflection and fiber deformation) of the concrete slab, caused by nonuniform distribution of moisture.
2. The effect of moisture changes on the modulus of rupture and compressive strength of concrete determined by tests of the beams, the dimensions of which were 4 inches by 7 inches by 4 feet, and cylinders 6 inches in diameter by 12 inches in length.
3. The volume changes in the concrete beam specimens due to exposure, including warping due to partial saturation.

CONCLUSIONS DRAWN FROM THE TESTS

From the results of the various studies the writer has reached the following conclusions:

1. The strength of concrete, like that of wood varies with its moisture content. While the law relating to moisture content and to strength was not determined throughout various ranges of moisture content, it appears that saturated concrete will have from 80 to 85 per cent of the strength of dry concrete.
2. The thermal coefficient of expansion of concrete varies with the temperature and moisture condition of the concrete.
3. Concrete expands when immersed in water and contracts on drying. The degree of change of length varies markedly with the characteristics of the brand of cement, with the richness of the mix, with the size of specimen, and with the conditions of exposure. Measurements begun after the initial hardening of the cement show that concrete may expand 0.01 per cent due to the absorption of moisture, and may contract 0.06 per cent when exposed to dry air. These changes continue. To these values should be added the changes in length during the initial setting of the cement.
4. Concrete road slabs warp upward at the corners and at the edges when the surface becomes dry, and also when the bottom absorbs moisture from the subgrade. Drying the top surface of the slab under observation deflected the corners upward 0.12 inch. When the bottom of the slab was saturated from a water-filled subgrade the upward corner deflection reached 0.20 inch.
5. This curling upward of the corners of the road slab presents a cantilever beam to the load of a passing truck. The results of the tests indicate the presence of an initial stress in the surface of the road slab arising from the warping.
6. A combination of shrinkage from drying and from a fall in temperature will produce maximum shrinkage strains. A combination of a drop in temperature and a rainfall may retain the concrete at its previous length. The friction of a road slab on its subgrade is an element favoring the production of cracks.
7. To be durable, concrete structures should be designed for the least favorable conditions. Stresses arising from the effect of temperature and moisture as well as those due to dead and live loads should be considered.
8. Without careful curing, concrete masses will undergo excessive surface shrinkage against their rigid cores, thereby favoring surface cracks. Therefore steel reinforcing should be placed near enough to the surface to withstand these shrinkage strains, and at the same time far enough below the surface to be protected against corrosion.
9. Foreign experiments show the benefit of early and careful curing of concrete in reducing final shrinkage. The greater part of the shrinkage of mortar specimens has been found to take place in the first 10 hours. These foreign experiments also show the greatly increased shrinkage of mortar mixed with an excess of water.
10. Since the results of measurements of expansion vary with several factors, such as the size of specimen, the time of initial measurement, and the exposure, the method of such tests should be standardized.

The writer believes that the following are the requirements for concrete structures exposed to the weather:

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[1] The substance of a paper presented at the meeting of the highway division of the American Society of Civil Engineers, New York, N. Y., Jan. 22, 1925.

[2] The tests were made under the supervision of the writer and Prof. R. B. Crepps. A. C. Benkelman was in direct charge, assisted by E. Gustavsen, both of the United States Bureau of Public Roads. R. E. Mills, of the Engineering Experiment Station of Purdue University, also assisted from time to time. Special acknowledgment is made of the painstaking care in observation and the devotion to the tedious program of measurements contributed by Mr. Benkelman.

[3] The approximate number of observations involved in the entire study was: Deformation, 40,000; deflection, 3,000; strength, 600; weight, 1,000; and temperature, 1,500.

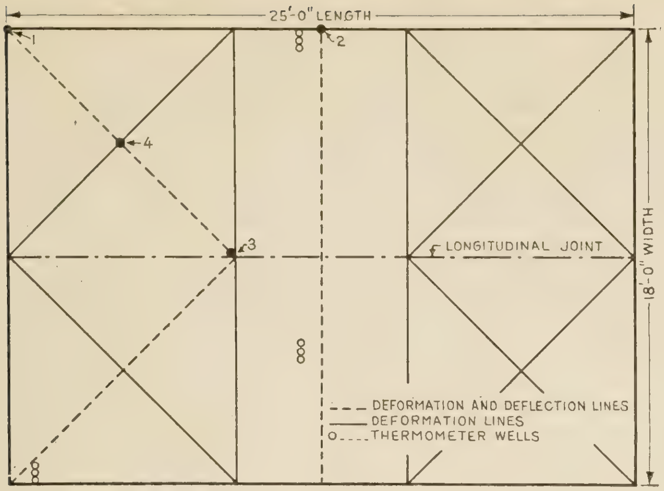

Fig. 2.—Plan of slab and observation layout

(*a*) A Portland cement of normal volume constancy and a clean, well graded aggregate.

(*b*) An impervious concrete of proportions not less than 1 :2 :4.

(*c*) A time of mixing of not less than 1 minute and preferably 1½ minutes for the production of uniform concrete.

(*d*) A concrete mixed with a minimum amount of water appropriate to the work at hand.

(*e*) Careful slicing of this plastic concrete against the face of the forms so that the reinforcing steel may not be exposed nor the surface require patching.

(*f*) Early curing begun just after the initial set and continued for a time depending on local conditions.

(*g*) Design of reinforcing steel and contraction or expansion joints to prevent cracking and the entrance of water.

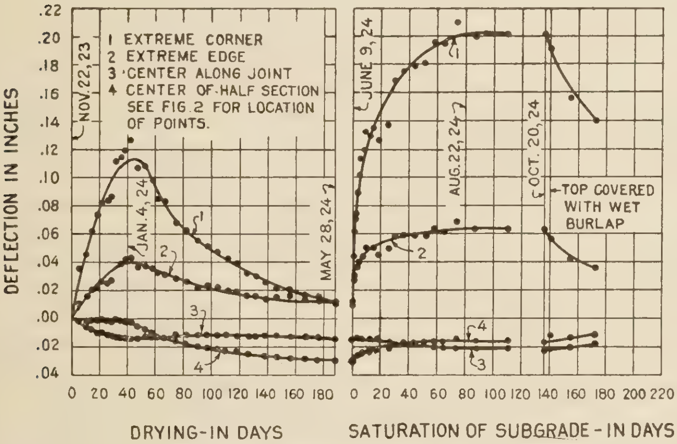

Fig. 3.—Deflections of road slab

DESCRIPTION OF THE TEST SLAB

The one-course concrete slab, made of 1 :1½ :3 concrete, was 7 inches thick, 18 feet wide and 25 feet long, with a longitudinal doweled center joint. A subgrade, consisting of a 4-inch layer of coarse gravel, was held in an impervious wooden subbase, the sides of which extended above the surface of the slab. The slab was housed in a shed and further protected by a tent. By means of perforated pipes in the gravel subgrade, through which warm air could be admitted, the subgrade could be dried; and water could be admitted to wet it again when desired. Warm, dry air was maintained above the slab in the tent enclosure.

Previous to the construction of the slab, concrete bench marks, for the support of the beams from which deflections were measured, were set 4 feet below the level of the ground. Rods extended upward from the bench marks through pipes set in the subgrade and slab. The slab and observation layout and the tent coverings are shown in Figures 1 and 2. Deformation measurements were made with 20-inch Berry strain guages; and deflections were measured with Ames dials reading to 0.001 inch.

THE EFFECT OF NONUNIFORM DRYING

The slab was cast on September 12, 1923, and was cured under water for 30 days. Following the curing period hot, dry air was forced under the slab through the perforated pipes in the gravel fill by a pressure fan; and, simultaneously, a drying atmosphere was maintained above the slab in the tent inclosure. Observations of the subsequent deformations and deflections, taken at weekly intervals, are shown in Figures 3, 4, 5, and 6.

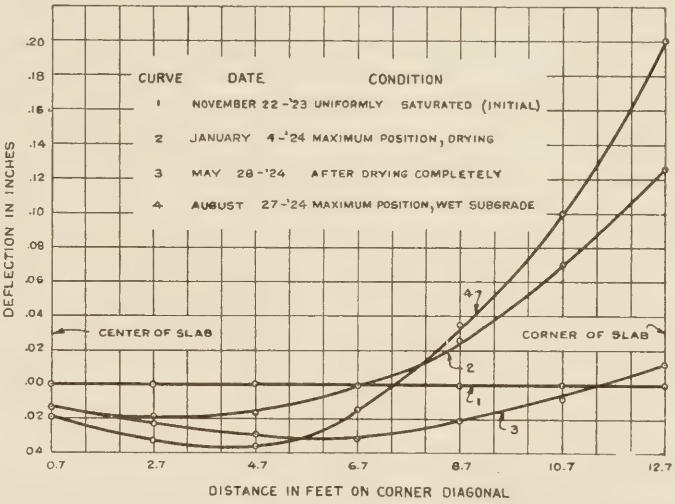

Fig. 4.—Typical profiles of the road slab showing effect of nonuniform moisture content

The more pronounced shrinkage occurring in the upper fibers was manifested by the fact that the edges and corners gradually curled up. A maximum uplift of 0.04 inch for the edges (at point 2, Fig. 3), and 0.12 inch for the corners (at point 1, Fig. 3), was attained at the end of 40 days. The subsequent return to a nonwarped or uniformly dry condition required five months. A slight permanent distortion as shown at point 3, Figure 4, representing the diagonal profile previous to the saturation of the subgrade is attributed to the more pronounced contraction of the richer troweled surface than the body of the slab. Observations were made of the longitudinal, transverse, and diagonal deformations of the upper surface of the slab. An average of two corner diagonals is shown in Figures 5 and 6.

All measurements of surface deformation of the slab were corrected for the changes in temperature which took place throughout the concrete. These temperature changes took place uniformly, that is, the readings of warping caused by the moisture gradient in the slab, were always taken when the temperature was uniform

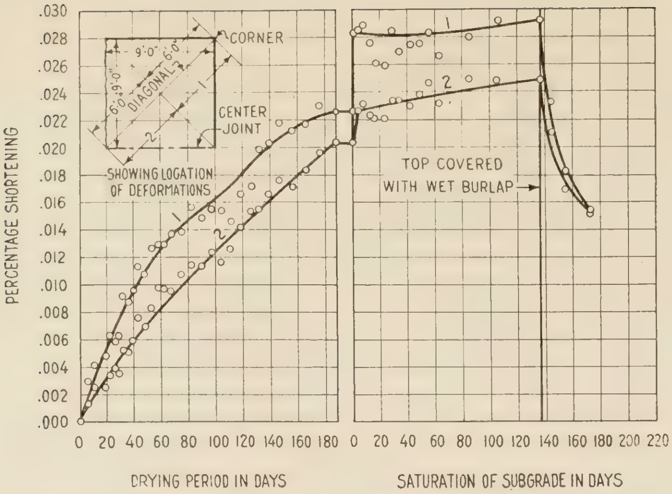

FIG. 5.—Deformation of upper surface of slab

throughout the depth of the slab; but there might be a rise or fall in temperature between the readings of two successive weeks. In this case the deformation readings were corrected for the temperature on the basis of a coefficient of expansion appropriate to the temperature of the concrete. (See Fig. 7.) The deformations shown in Figure 5 are therefore the net values after the corrections have been applied. Figure 6 shows the actual and corrected deformations, together with the changes in the temperature of the slab (uniform throughout the depth of the concrete). As the temperature changes were uniform throughout the depth of the slab there appears to be no reason for any correction of the vertical deflections caused by the moisture gradient.

The total diagonal contraction due to the moisture gradient between the condition of saturation (November 22, 1923) and that of completely dried concrete (May 28, 1924) was 0.021 per cent (Fig. 6). This value, like all others, has been corrected for uniform temperature changes. As will be shown later, beams of 1:1½:3 concrete contracted 0.022 per cent in 160 days. Hence, it appears that friction of the subgrade did not restrain the movement.

The fact that some of the points fall off the curve in Figure 3 is attributed to a slight effect of temperature in the warping of the slab, that is, they indicate that the contemplated procedure which called for the taking of observations only at times when the temperatures were uniform from top to bottom of slab, was not completely complied with.

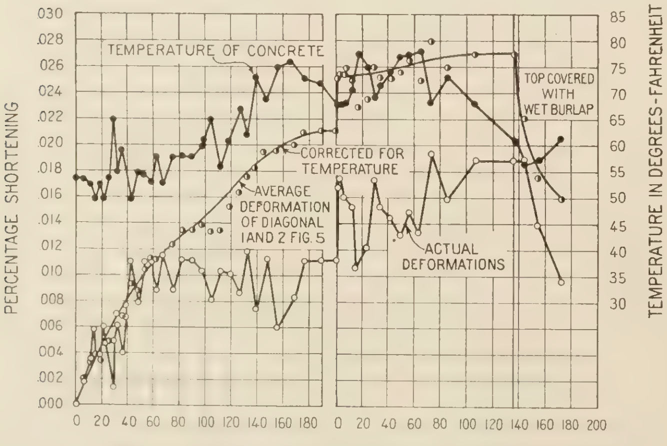

FIG. 6.—Temperature of slab and actual and corrected diagonal deformations

THE EFFECT OF NONUNIFORM SATURATION AND TEMPERATURE VARIATIONS

Following the drying period, water was introduced into the gravel subbase and maintained level with the lower surface of the slab. Differential expansion from bottom to top was again manifested in an immediate and continued gradual curling up of the edges and corners. A maximum distortion of 0.066 inch for the edges and 0.202 inch for the corners was attained at the end of 3 months. Typical results of the observations from June 2, 1924, the date of starting the saturation tests, until October, 1924, are shown in Figures 3, 4, 5, and 6.

While the subgrade was being resaturated the surface contracted diagonally 0.007 per cent in 110 days as shown by Figure 5. Of this contraction 46 per cent took place in 2 hours and nearly 100 per cent in 2 days. The shortening was caused by the expansive force of the saturated lower part of the slab, and occurred without a change in moisture content or temperature of the top layers. Assuming an elastic condition and a modulus of elasticity of 5,000,000 pounds per square inch, a compressive stress of 350 pounds per square inch in the top is indicated.

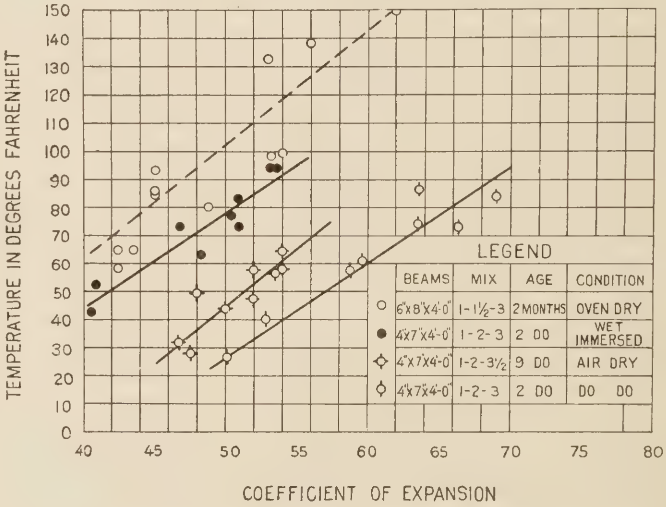

FIG. 7.—Thermal coefficient of expansion of concretes at different temperatures

When the slab had reached a static condition with saturated subgrade (on Oct. 20, 1924), an attempt was made to expand the surface by applying saturated burlap to simulate the effect of prolonged rain. In 30 days the corner had dropped 0.060 inch to a deflection of 0.140-inch (see Fig. 3), and the diagonal deformation had been reduced 0.014 per cent (Fig. 5).

The effect of daily variations of temperature in the air above the slab (not the outdoor temperature) is shown in Figure 8. A rise in temperature of 41° F. from 8 a. m. to 3 p. m. warped the corner downward 0.023 inch, or 21 per cent of the total warping (0.11 inch) at that period. While the air temperature changed from 34° F. to 75° F., the temperature of the top of the slab changed from 44° F. to 49° F., and that of the bottom of the slab from 47° F. to 49° F., a temperature differential of 3° F., which was the cause

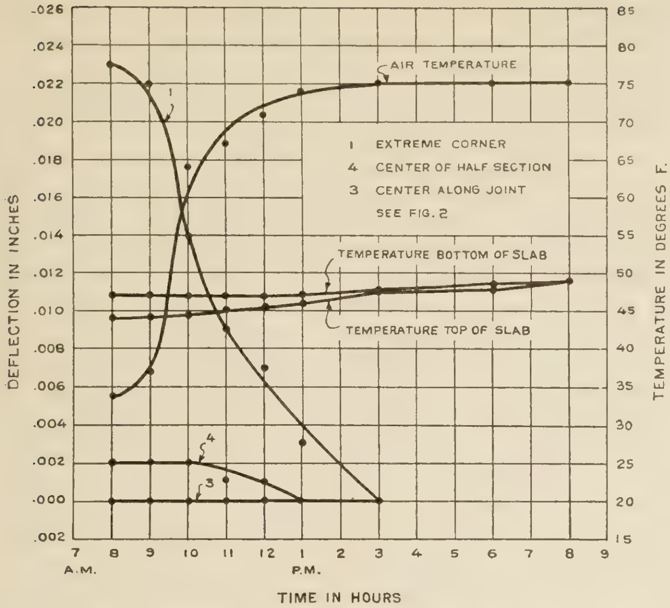

Fig. 8.—Deflection of road slab caused by temperature changes

of the warping. This warping may be compared to the deflection of 0.202 inch caused by the nonuniform saturation of the slab by the wet subgrade.

LOAD TESTS ON THE SLAB

Known loads were applied to one corner of the slab by jacking at three stages of the test: (1) On June 14, 1924, during the drying stage; (2) on September 23, 1924, during the saturation of the subgrade; and (3) on November 14, 1924, when the top had been saturated 25 days with wet burlap. The profiles of the diagonal on these dates for a load of 3,000 pounds are shown in Figure 9. The deflection data are given in Table 1. The deformation along the diagonal under the three conditions varied from 0.000031 inch per inch to 0.000037 inch per inch, the greatest deformation corresponding to the load applied during the drying period and the least to the load applied when the surface had been saturated with wet burlap.

As the warping of the slab increased (see (2), Fig. 9) the point of support must have moved in, increasing the deflection under load. Curiously enough, the deflection of the slab under load when the top was wet was less than in either of the other two cases.

TESTS OF CONCRETE MATERIALS

Six brands of cement were tested in connection with the various investigations of beams, compressive cylinders, and the road slab. These brands are designated in the reports of the tests which follow, as A, B, C, D, E, and F.

In the road slab cements A and D were mixed in equal parts and combined with sand and gravel in the proportions of 1:1½:3 for one half-section of the slab. For the other half, brand F was mixed with the same aggregates in the same proportions. In some of the beams cement F was used with the same aggregates in the proportions of 1:2:3½. The results of the usual standard tests of the cements used in the beams and slab are given in Table 2.

Table 1.—*Deflection of slab due to corner load of 3,000 pounds*

	Condition		
	During drying	Bottom wet	Top wet
Corner level, in inches:			
Before load	0.0131	0.0183	0.0124
With load	.0077	.0120	.0091
Deflection due to load	.0054	.0063	.0033
Set due to load, after 5 minutes	.008	.009	.008
Percentage of elongation under stress (in distance of 48 inches adjacent to the corner):			
Diagonal	.0037	.0035	.0031
Edges	.0025	.0023	.0017

The aggregates were washed sand and gravel from the Western Indiana Sand & Gravel Company, at La Fayette, Ind. The results of the sieve analysis and miscellaneous tests of the aggregates are given in Table 3.

The coarse aggregate was separated into three sizes: Between the 2-inch and 1-inch screens; between the 1-inch and ½-inch screens; and between the ½-inch and ¼-inch screens. It was then recombined in such proportions as to give maximum density according to Fuller's maximum density curve. The consistency of the mix was checked by the slump-cone method. All materials, including water, were weighed for each batch. The properties of the concrete are listed in Table 4.

Expansion and contraction of cements.—Changes in the length of specimens made of the six brands of cement neat, and a mixture of brands A and D, and concrete specimens made with brand F and the mixture of A and D, were made with Berry extensometers. The specimens of neat cement were 2 by 2 by 24 inches, those of concrete were 4 by 7 inches by 4 feet. The measurements were made for the purpose of ascertaining the expansion and contraction of the specimens on immersion in water and subsequent exposure to air. Measurements began two days after moulding, with previous moist-chamber storage. The results are shown in Table 5 and Figures 10, 11, and 12.

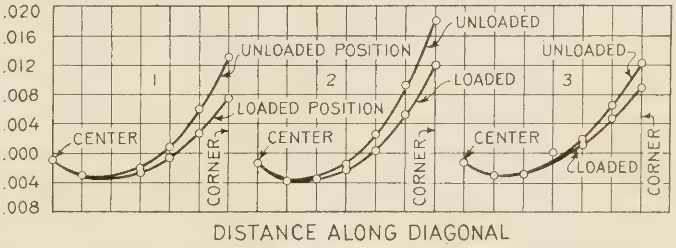

Fig. 9.—Deflections of corner diagonal of slab under 3,000-pound corner load

Table 2.—*Tests of cement*

Brand	Percentage of water		Percentage retained on 200-mesh sieve	Time of setting				Soundness	Tensile strength	
	Normal consistency	Mortar		Initial		Final			7 days	28 days
				Hrs.	*Min.*	*Hrs.*	*Min.*		*Lbs.*	*Lbs.*
A and D mixture, equal quantities	24	10.5	[1] 17.17	2	10	5	15	O. K.	297	373
D	23	10.3	[1] 20.3	2	35	5	20	O. K.	242	326
A	24	10.5	[1] 22.6	4	00	5	55	O. K.	255	327
F	25	10.7	19.1	3	35	5	15	O. K.	220	333

[1] Different samples.

Table 3.—*Tests of aggregates*

Unit weight of coarse aggregate =102.5 pounds per cubic foot.
Unit weight of fine aggregate =106.8 pounds per cubic foot.
Fineness modulus of coarse aggregate =7.32.
Fineness modulus of fine aggregate =3.17.
Fineness modulus of combined aggregate =5.90 for a 1:1.5:3 mix.
=5.77 for a 1: 2: 3.5 mix.

SIEVE ANALYSIS OF GRAVEL

(Tyler standard sieves)

	Total percentage retained on each sieve								
Sieve sizes	1½ in.	¾ in.	⅜ in.	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100
Percentage	0	46	87	98	99	99	99	99	100

SIEVE ANALYSIS OF SAND

(Tyler standard sieves)

	Total percentage retained on each sieve						
Sieve sizes	⅜ in.	No. 4	No. 8	No. 14	No. 28	No. 48	No. 100
Percentage	0	0	3	38	77	97	99

Table 4.—*Tests of concrete*

Slump (4 to 8 by 12-inch truncated cone) =1 to 1½ inch.
Water-cement ratio =0.809 for a 1:1½:3 mix.
Water-cement ratio =0.935 for a 1:2:3½ mix.
Specific gravity =2.68.
Density =0.896.
Percentage of voids =10.4.
Percentage of absorption by weight =4.29.
Average unit weight, both concretes:
Oven dried to constant weight =149.89 pounds per cubic foot.
Immersed in water to constant weight=156.32 pounds per cubic foot.
Air dried in laboratory for 135 days=151.89 pounds per cubic foot.

Expansion due to termperature.—The coefficient of temperature expansion of four concretes was measured, with the results shown in Figure 7. The temperature of the concrete was obtained from blank beams in which there were thermometer wells consisting of steel pipes filled with a light paraffin oil. The thermometers were graduated to one-fifth of a degree. Reading from the left, the chart covers: (1) Three beams 6 inches by 8 inches by 4 feet, 1 : 1½ : 3 mix, age 2 months, cured under wet burlap during 30 days, and dried in oven at 150° F. for 21 days; the beams were taken from the oven and readings taken at 20° F. intervals as the temperature dropped, four cycles were read on as many days. (2) Two beams, 7 inches by 4 inches by 4 feet, 1 : 2 : 3 mix, age 2 months, kept immersed in water the temperature of which was varied and held constant 2 hours before observation. (3) Three beams, 4 inches by 7 inches by 4 feet, 1 : 2 : 3½ mix, age 9 months, cured under wet burlap for 14 days oven-dried for 1 month and air-dried for 7½ months; beams were moved from warm laboratory air to cold air of shed. (4) Two beams, 4 inches by 7 inches by 4 feet, 1 : 2 : 3 mix, age 2 months, cured under wet burlap for 14 days, in air 6 weeks. The various curves indicate that the variation of the coefficient of thermal expansion varies with the temperature range under observation.

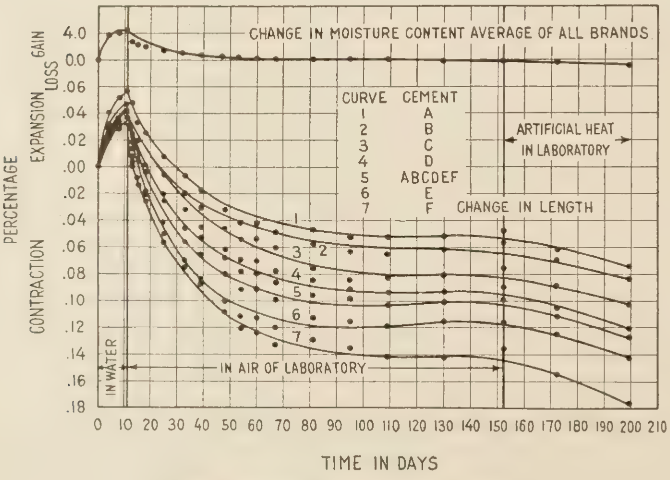

Fig. 10.—Contraction of neat cements, air-dried

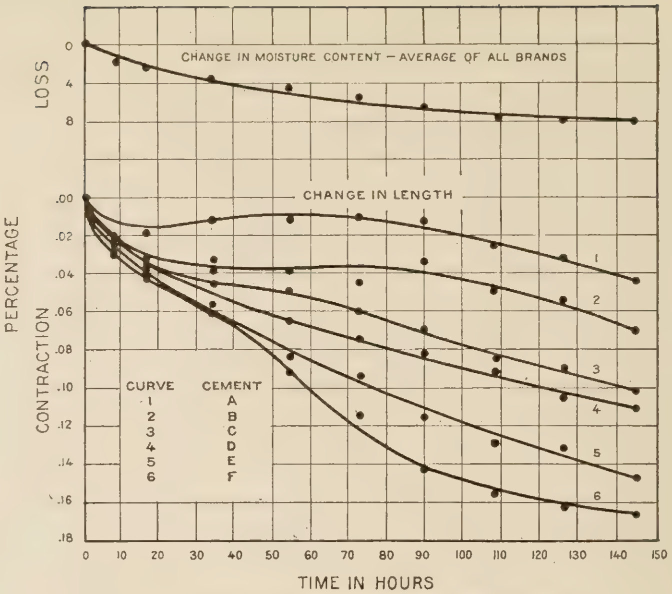

Fig. 11.—Contraction of neat cements, oven-dried at 150° F

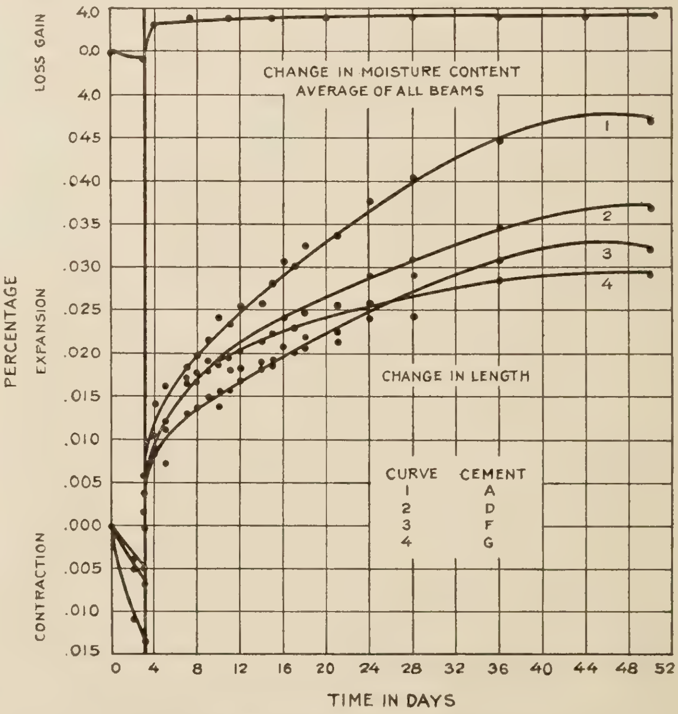

Fig. 12.—Expansion of neat cements, cured in water

The thermal coefficient of expansion of the several brands of cement tested neat was as follows:

Brand	Age 4 months; dry in air. Range 50°–73° F.	Age 2 months; under water. Range 52°–90° F.
1	0.0000096	0.0000094
2	.0000094	------
3	.0000092	.0000087
4	.0000090	------
5	.0000089	------
6	.0000083	------
7	.0000085	.0000085

TABLE 5.—*Expansion and contraction of neat cements and concretes*

	Expansion and contraction of brands						
	A	B	C	D	E	F	Average of A and D
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Neat cement:							
Percentage of water for normal consistency	24.00	24.00	22.00	23.00	23.00	25.00	------
Percentage retained on 200-mesh sieve	17.53	22.86	20.38	23.90	16.24	19.14	------
Percentage of expansion in water, 10 days	+0.056	+0.044	+0.040	+0.036	+0.034	+0.030	+0.048
Percentage of contraction in air, 90 days (subsequent to immersion)	−.052	−.062	−.080	−.094	−.114	−.142	−.073
Total percentage of change	.108	.106	.120	.130	.148	.172	.121
Net percentage of change	+.004	−.018	−.040	−.058	−.080	−.112	−.025
Concrete:							
Gravel concrete, 1 : 2 : 3½—							
Percentage of expansion in water, 40 days	------	------	------	------	------	+0.005	------
Percentage of contraction in air, 90 days	------	------	------	------	------	−.035	------
Percentage of change, 40 days in water, 90 days in air, 20 days in oven	------	------	------	------	------	−.040	------
Percentage of change, 40 days in water, 90 days in air, 30 days in oven	------	------	------	------	------	−.050	------
Gravel concrete, 1 : 1½ : 3—							
Percentage of expansion in water, 40 days	------	------	------	------	------	------	+.0050
Percentage of contraction in air, 90 days	------	------	------	------	------	------	−.0150
Percentage of change, 40 days in water, 90 days in air, 20 days in oven	------	------	------	------	------	------	−.02
Percentage of change, 40 days in water, 90 days in air, 30 days in oven	------	------	------	------	------	------	−.0225

A comparison of the basic water content and voids in the cement paste at this basic water content would no doubt throw light on these differences in the changes of length and in the quantity of water required for standard consistency and the fineness or percentage retained on the 200-mesh screen, which are also noted in Table 5. The basic water content, as defined by A. N. Talbot, past president American Society of Civil Engineers, is the percentage of water at which the voids are a minimum.

It appears that those cements which expand most in water subsequently contract least in air. The neat cement prisms expanded in water nearly ten times as much as the concrete beams; in air they contracted nearly five times as much as the concrete.

TESTS ON BEAMS

Subsidiary to the tests on the slab and designed to supplement the slab observations, tests were conducted on beams and cylinders. Two classes of beam tests were made: (1) On beams warped by nonuniform saturation; and (2) on beams uniformly saturated.

In the tests of the slab it was possible to measure the deflection and deformation of the top of the slab, but there were no means available for the measurement of bottom deformations. To provide means of estimating the bottom deformations from the measured top deformations and deflections, a study was made of similar deformations observed in the warped beams. The size of these beams, 4 inches by 7 inches by 4 feet, was chosen to give a thickness equal to that of the road slab. After initial drying the beams were placed with the bottom in contact with wet burlap and successive observations of deformation and corresponding deflections were made. Deformations were recorded at seven different depths between two pairs of specimens in each beam. The average results for three beams are shown in Figure 13, A. During nine days the lower face expanded 0.0152 per cent and the upper face shortened 0.0024 per cent. The data locate the position of the neutral axis of deformations and show the relative deformations occurring throughout the depth of the beam. The height to which the saturation, visually observed, proceeded at the end of nine days was approximately 2⅔ inches, or one-third the depth of the beams.

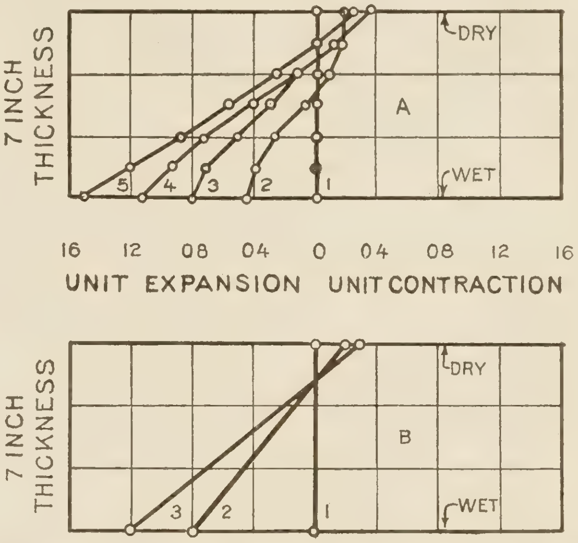

FIG. 13.—Measured deformations of beams and calculated deformations of road slab

The relative top and bottom deformations referred to above were actually observed in the test beams. To interpret the results of the slab tests, however, it is necessary to establish a relation between the top deformation and deflection and the deformation of the bottom; and it appears that a mathematical relation does exist which conforms closely with the measured values as obtained from the beams.

If the curve of distortion of the warped beams be assumed to be an arc of a circle, the following formula is applicable:

$$\epsilon_T+\epsilon_B=\frac{8\,h\,m}{L^2} \qquad (1)$$

in which—

ϵ_T = the unit deformation of the top of the beam.
ϵ_B = the unit deformation of the bottom of the beam.
h = the depth of the beam.
m = the deflection of the beam.
L = the length over which the deflection occurs.

In checking the measured deflections against the measured deformations of the beams it is found that the calculated values agree closely with the measured values.

For example, in the condition represented by curve 5, Figure 13, A, the unit expansion of the lower face of the beam was 0.0152 per cent; the unit contraction of the upper face corresponding was 0.0024 per cent; and the corresponding measured deflection was 0.0048 inch. Substituting the observed values of the unit deformations in Equation 1, the computed deflection is

$$0.000024+0.000152=0.000176=\frac{8 \times 7 \times m}{1600},$$

from which

$$m \text{ (the deflection)} = 0.0050 \text{ inch}$$

Application of formula to road slab data.—In Table 6 measured values of deformation and deflection of the top surface of the road slab are given and the corresponding bottom deformations resulting from the flooding of the subgrade are computed by substitution of the measured values in Equation 1. The curves referred to are those of Figure 13, B, and all steps in the calculation are shown.

Table 6.—*Computation of bottom deformations of road slab*

Curve	Condition	Measured unit contraction of top	Measured deflection over 40-inch span
		Per cent	*Inches*
1	Uniformly dry	0.02	0.0000
2	Bottom wet, 11 days (interior section)	.0019	.0028
3	Bottom wet, 11 days (exterior section)	.0028	.0042

Substituting in equation 1,

$$\epsilon_T+\epsilon_B = 0.00010 \text{ for curve 2}$$
$$.00015 \text{ for curve 3}$$

$$\text{And, by measurement, } \epsilon_T = .000019 \text{ for curve 2}$$
$$.000028 \text{ for curve 3}$$

$$\therefore \epsilon_B = .00008 \text{ for curve 2}$$
$$.00012 \text{ for curve 3}$$

The computed values of ϵ_B are plotted in Figure 13, B, with the measured values of ϵ_T corresponding. The figure clearly indicates the swelling of the bottom and the shortening of the top of the slab. A neutral axis of deformations separates the two, similar to that observed in the subsidiary beams. The greater swelling of the concrete at the unrestrained edge of the slab, and the lesser swelling at the interior restrained positions is shown.

The translation of the measured deformations into stresses, and the variation of such stresses throughout the cross-section, is a field of discussion of considerable interest. The corners of the slab are held up against the dead weight of the overhanging cantilever, which has been raised by the swelling of the bottom concrete. What is the state of stress in the top which has been shortened?

THE STRENGTH OF WARPED BEAMS

In addition to the above observations on warped beams, they were also used to determine the progress of saturation from the bottom upward, and the effect of the warping on their transverse strength.

Table 7.—*Modulus of rupture data of warped beams*

Number of beams	Initial contraction	Condition at time of test	Visual height of water	Deformation at time of test		Face loaded in tension	Modulus of rupture, cantilever loading			Modulus of rupture, third-point loading			Modulus of rupture percentage of grand average
				Wet face	Dry face		Number of values	Numerical values	Percentage of reference values	Number of values	Numerical values	Percentage of reference values	
Series No. 1. 6 inch by 8 inch by 4 foot beams. 1:1½:3 mix. Cements A and D. Age, 4 months. Oven dry.													
	Per cent		*Inches*	*Per cent*	*Per cent*								
5	0.022	Dry					20	720	100				100
2	.022	Saturated		+0.020			10	616	85				85
5	.022	Saturated to 2-inch depth	3	+ .019	−0.0016	Dry.	19	789	109				109
5	.022	do	3	+ .019	− .0016	Wet.	19	602	83				83
Series No. 2. 7 inch by 4 inch by 4 foot beams. 1:2:3½ mix. Cement F. Age, 3 months. Air-dry.													
3	0.041	Dry					8	839	100	3	738	100	100
3	.041	Saturated		+0.017			8	672	80	2	506	68	77
4	.041	Saturated to 2⅓-inch depth	3½	+ .024	+0.0035	Dry.	12	750	89	4	614	83	87
4	.041	do	3½	+ .024	+ .0035	Wet.	12	618	73	4	472	64	71
Series No. 3. 7 inch by 4 inch by 4 foot beams. 1:2:3½ mix. Cement F. Age, 3 months. Oven dry.													
8	0.049	Dry					20	780	100	7	652	100	100
7	.049	Saturated		+0.018			19	671	85	5	544	83	85
3	.049	Saturated to 2½-inch depth	4	+ .021	+0.016	Dry.	10	637	81	3	511	78	80
3	.049	do	4	+ .021	+ .016	Wet.	10	609	78	3	478	72	76
Series No. 4. 7 inch by 4 inch by 4 foot beams. 1:2:3½ mix. Cement F. Age, 7 months. Oven dry, 3 months; Air-dry, 4 months.													
1	0.037	Dry					4	809	100	1	651	100	100
1	.041	Saturated		+0.014			3	699	86	1	553	85	86
1	.043	Saturated to 1½-inch depth	3½	+ .017	−0.004	Dry.	3	961	118	1	742	114	117
2	.040	Saturated to 2¾-inch depth	4	+ .015	+ .0003	Dry.	7	774	95	1	646	99	96
1	.040	Saturated to 4-inch depth	5	+ .018	+ .0017	Dry.	3	670	82	1	565	86	83
Series No. 5. 7 inch by 4 inch by 4 foot beams. 1:2:3½ mix. Cement F. Age, 7 months. Air-dry.													
2	0.051	Dry					6	825	100	2	731	100	100
1	.047	Saturated		+0.021			3	733	88	1	633	86	88
1	.048	Bottom wet	2	+ .020	−0.0065	Dry.	3	1,066	129	1	884	121	127
2	.052	Saturated to 1¼-inch depth	2½	+ .027	− .0048	Dry.	6	910	110	2	734	100	107
1	.054	Saturated to 2½-inch depth	3½	+ .032	+ .0012	Dry.	4	714	86	1	651	89	87

The beam specimens were dried to constant weight. Some were then entirely immersed in water and others were immersed to only a fraction of their depth.

The changes in weight, length, and strength were determined for the different conditions. Five separate series of such experiments were conducted, varying the proportions of the mix, the brand of cement, the extent and nature of drying, and the depth of partial saturation. The results are shown in Table 7.

Results of beam tests.—By reference to Table 7 a comparison of beams uniformly saturated shows that the expansion in water varies from 0.014 to 0.021 per cent with an average of 0.018 per cent. These beams were immersed for 5 days subsequent to the initial drying. The 1 : 2 : 3½ concrete made with cement F when air-dried for 2½ months contracted 0.041 per cent.

The 1 : 1½ : 3 concrete, made with cements A and D mixed, after conditioning by 30 days curing under wet burlap, followed by complete oven drying, contracted 0.022 per cent.

The reduction in strength from completely dried concrete to uniformly saturated concrete in the five cases ranges from 12 to 23 per cent, an average of 15.4 per cent.

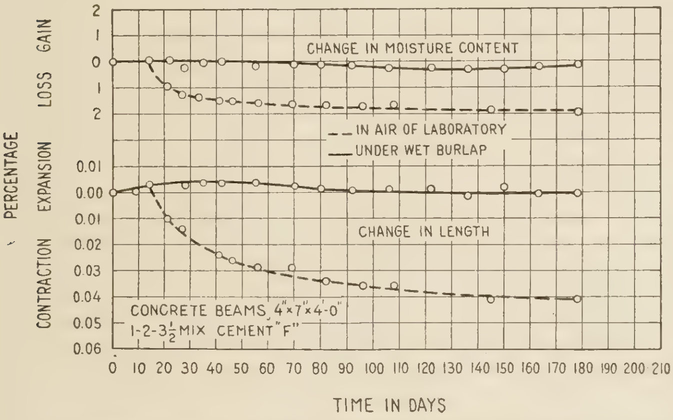

Fig. 14.—Change in length compared with change in moisture content of concrete beams made with cement F

Certain beams were warped by saturation from the bottom upward to increasing heights (see Table 7), as determined by visual observations of the broken beams and by weighing.

Contractions from 0.0016 to 0.0065 per cent were developed in the dry face, and expansions from 0.015 to 0.032 per cent at the wet face of the warped beams. When these warped beams were broken with the contracted dry side in tension, an increase from 9 to 29 per cent in strength over the entirely dry beam was indicated, depending on the amount of initial contraction.

When saturation had proceeded to a greater height in the beams (approximately 2 inches from the top), the area of dry concrete became too small to hold back the expansion of the wet area, and, consequently, the dry face was actually elongated by the force of the expanding face. When the expanded dry face was tested in tension, the beams were only 81 to 95 per cent as strong as the uniformly dry beams; when turned with the wet side in tension the percentage was 73 to 83. The complete data are given in Table 7.

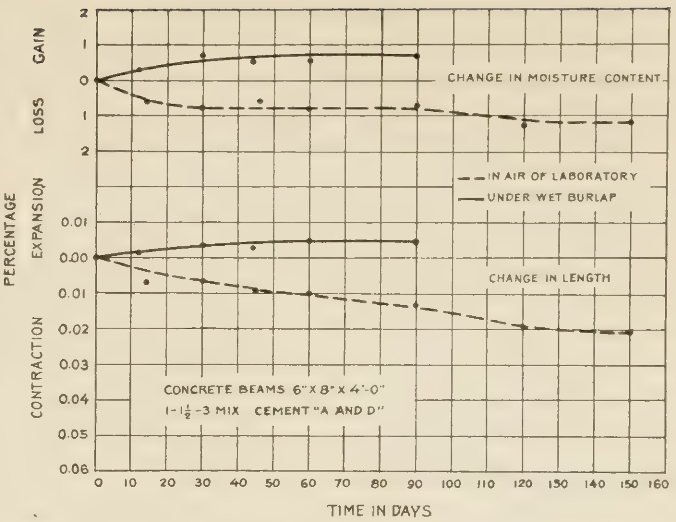

Fig. 15.—Change in length compared with change in moisture content of concrete beams made with cements A and D

The writer accounts for this increase in strength of warped dry faces when they have been shortened and the decrease in strength when they have been lengthened by the absorption of moisture on the opposite face by the presence of an initial compression in the former and of an initial tension in the latter case. However, an analysis of moduli of elasticity and the deformations of the top and bottom face of the beams, tested under the third point loading, fails to show any substantial difference between the extensibility at rupture or 50 per cent of rupture of the beams with the dry face either shortened or lengthened by warping. The neutral axis in all these loaded warped beams is nearer the compression than the tension face (wet or dry) at 50 per cent of rupture and also at rupture. The maximum extensibility in tension was from 0.015 to 0.018 per cent. The simultaneous compression was from 0.012 to 0.016 per cent.

To assume an initial stress would presuppose an elastic concrete holding this stress throughout the five days previous to test, and an unusual distribution of stresses throughout the cross section. Inasmuch as these initial stresses must balance, it is hard to reconcile an initial compression in the top with a compression in the saturated bottom. This matter is left open for discussion.

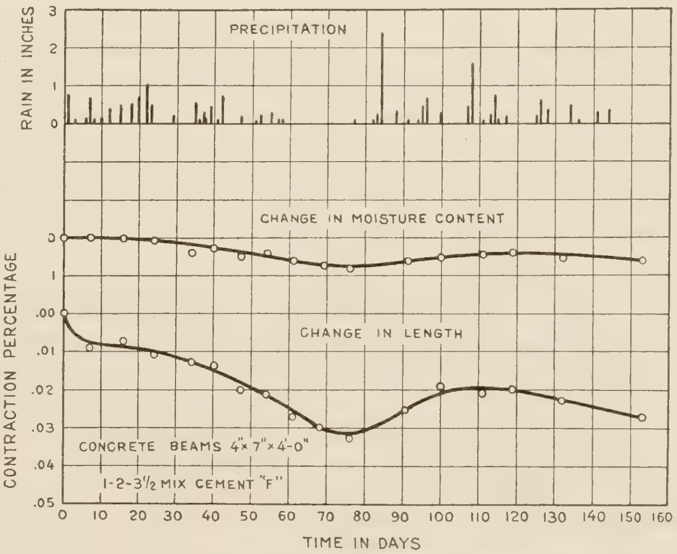

Fig. 16.—Contraction of concrete exposed to weather

TESTS OF UNIFORMLY SATURATED BEAMS AND CYLINDERS

In addition to the tests of warped beams a series of tests was made on beams and compressive cylinders with uniform moisture content. This series included the study of the following phenomena:

Length changes resulting from:
1. Continuous immersion in water.
2. Continuous exposure to air in the laboratory.
3. Continuous exposure to weather.
4. Oven drying at 150° F.
5. Immersion of oven-dried and air-dried specimens.

Transverse strength determinations as to:
1. Decrease due to uniform saturation.
2. Changes due to age and treatment.
3. Effect of freezing temperatures on saturated and dry concrete.

Compressive strength tests for:
1. Increase due to age and treatment.

The size of the beam specimens was 4 by 7 inches by 4 feet. In the initial series of tests concrete similar to that of the road slab was investigated, namely, a 1:1½:3 mix, using cements A and D. In a later series of tests, cement F was used, the mix being 1:2:3½.

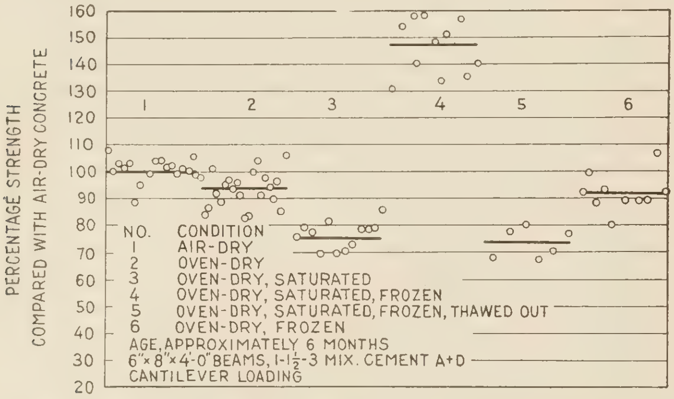

FIG. 17.—Effect of saturation and freezing on the transverse strength of beams

Length changes of beams.—Measurements of changes in length of the beams due to moisture were begun two days after moulding. A 20-inch Berry strain gauge, used in the measurements, was compared to a standard invar steel bar, maintained at a constant temperature. Six gauge lines were set in each beam, three on the top and three on the bottom. The results are the average of measurements on at least four beams. Corrections for the influence of temperature were made from observations of the temperature of two auxiliary beams, the thermal coefficient of which was previously measured.

Figures 14 and 15 show the percentage changes in moisture content and the corresponding change in unit length of the concrete. The 1:2:3½ concrete, cement F (Fig. 14), expanded 0.0050 per cent after a continuous curing under saturated burlap for 40 days and contracted 0.0035 per cent after 90 days in air. The 1:1½:3 concrete, cements A and D (Fig. 15), expanded 0.0050 per cent after a similar curing for 40 days and contracted 0.015 per cent after 90 days in air. Thus, considerable variation is evident in the degree of length change of the two concretes as affected by the character of the cement.

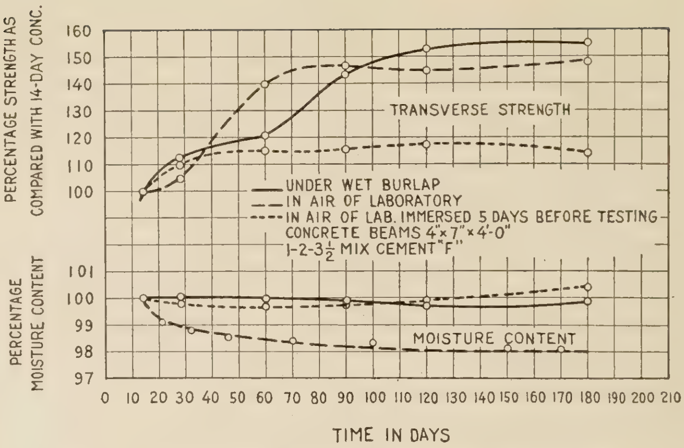

FIG. 18.—Effect of age and treatment on transverse strength of beams

Additional beams of concrete, using cement F, were exposed to the weather. Changes in length and weight and the amount of rainfall were observed, as shown in Figure 16. A maximum contraction of 0.033 per cent occurred in 75 days. Beams of similar concrete exposed to the air of the laboratory for the same period of time also contracted 0.033 per cent.

Transverse strength.—The beams were tested (1) by loading at the third points, the span length being 42 inches; and (2) by loading them as cantilevers.

In the former case, the deformations of the top and bottom faces were measured by 10-inch Berry strain gauges; in the latter, one end of the beam was fixed between the bed and the movable head of a testing machine and broken near the section of support by means of an attached lever arm 5 feet in length. In this manner a number of sections of one beam may be broken consecutively. To load the testing machine shot was allowed to flow into a bucket. The halves of the beams broken under the third-point loading were also tested under cantilever loading.

Figure 17 shows the relative strength values of a series of tests on concrete beams made with cements A and D. A 20 per cent reduction results from saturation. An increase of approximately 100 per cent in strength appears when saturated concrete is tested in a frozen condition. This is due to the strength of the ice. The percentage relation is based on air-dried concrete.

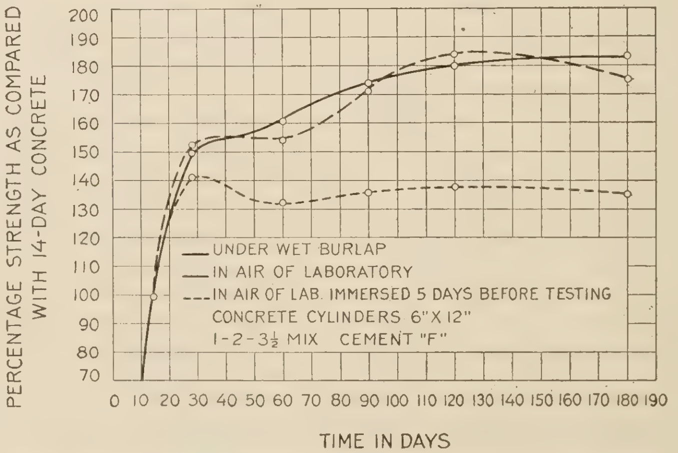

FIG. 19.—Effect of age and treatment on compressive strength of concrete cylinders

In Figure 18 the effect of age and moisture on the transverse strength of beams is shown. The specimens that were cured continuously under wet burlap and those air-dried, but subsequently saturated, contain approximately the same quantity of water by weight. The latter, however, are consistently 19 per cent lower in strength on a direct basis than the former at an age of 90 days. All the specimens were made at the same time, and then exposed to varying conditions. Each plotted point in Figure 18 represents the average of 12 tests.

No doubt the water is concentrated to some extent at the surface of the samples that are air-dried, but subsequently saturated. The appearance of the broken specimens, however, indicated uniform moisture distribution.

Compressive strength.—Cylinders 6 inches in diameter by 12 inches long were capped with plaster of Paris and tested in compression. Deformations were measured up to about one-half the ultimate strength by means of ring compressometers, with the results shown in Figure 19, which checked the findings in the case of the beams. Each plotted point represents the average of three tests.

Aggregate failures occur with consistent regularity in the case of the air-dried or oven-dried specimens, likewise with specimens cured continuously under damp burlap; in the case of the saturated concrete, however, the failures are invariably due to bond between the mortar and the aggregate.

REVIEW OF LITERATURE

A review of the literature on the expansion and contraction of cements, mortars, and concrete has been made in connection with the Purdue University investigations, and a digest appears in the paper as presented by the writer at the meeting of the highway division of the American Society of Civil Engineers, at New York, on January 22, 1925.

CURING CONCRETE WITH CALCIUM CHLORIDE

By **C. L. McKESSON,** Materials and Research Engineer, California Highway Commission

One of the difficulties attendant upon the construction of concrete pavements in the drier regions of California is the expense of securing water for curing the concrete for two weeks after laying. It has long been known that calcium chloride, under favorable conditions, will absorb moisture from the air and, during recent years, experiments have been made in an effort to utilize this chemical as a substitute for ordinary water curing. Illinois, with a rather high relative humidity and precipitation throughout the year, reports considerable success in the curing of concrete by distributing 2½ pounds of calcium chloride per square yard soon after the concrete is finished.

During the last year the California Highway Commission has conducted extensive field and laboratory experiments in an endeavor to ascertain whether this substitute can be used safely in California in sections where humidity is low, temperature high, and precipitation absent during summer months. Field experiments were conducted on paving jobs in Los Angeles, Ventura, Sacramento, and Humboldt Counties.

Preliminary experiments made early in the season indicated that a slight reduction in strength would probably result from the substitution of calcium chloride treatment for the usual water curing and all of the field tests made during the summer bore out this conclusion.

On two of the projects concrete specimens 6 by 6 by 12 inches were cast from the concrete actually used in the pavement. In each case half of the specimens were cured by placing them on one side the morning after they were made and by applying flake calcium chloride (dry) at the rate of 2½ pounds per square yard of surface. The other half were water cured. On three jobs, a portion of the pavement was treated in a similar way with calcium chloride and the remainder was cured with water in the usual manner. After the completion of the work cores were drilled from the pavement cured by both methods. The cores were tested by the State highway laboratory at Sacramento.

Following is a summary of the results of the tests and relative efficiency of calcium chloride curing as indicated by them.

Location of experiment	Number of samples	Average compressive strength				Efficiency of calcium chloride[1]	Remarks
		6 by 6 by 12-inch molded specimens		4½-inch cores from pavement			
		Cured with water	Cured with calcium chloride	Cured with water	Cured with calcium chloride		
				Lbs.	*Lbs.*	*P. ct.*	
(X-Sac.-4-B) Sacto-Stockton highway, near Sacto.	24	-------	-------	4,292	4,218	98	Hot and dry (water-cured concrete 57 days old. Concrete cured with calcium chloride 70 days old).
(VII-L. A.-2-BO) Ventura-Los Angeles highway near Calabasas.	32	3,064	2,783	-------	-------	91	Hot and dry.
	28	-------	-------	4,057	3,294	81	
(VII-Ventura-2-A) Los Angeles highway near Newbury Park.	12	-------	-------	3,491	3,093	88	Hot and dry.
(I-Hum.-1-GH) Eureka-Arcata highway at Arcata.	72	3,887	3,545	-------	-------	92	Experiment in October. Weather cool, humidity high (70 to 90 per cent). Some rain.

[1] Efficiency of calcium chloride curing, assuming water curing to be 100 per cent efficient.

The above tests indicate that calcium chloride is from 80 to 90 per cent efficient and that it might be used as a substitute for water curing where water is scarce. Some of the strength appears to be sacrificed, but the cores showed a minimum average strength of more than 3,000 pounds in the most unfavorable case, and this strength indicates a fair factor of safety.

A very extensive series of curing tests not included in the above discussion was conducted at Sacramento during the summer and fall of 1924 by the California Highway Commission in cooperation with the Structural Materials Research Laboratory of Lewis Institute. Calcium chloride and many other methods of curing were included in this series, the results of which will be given to the public in a report now being prepared.

VERTICAL PRESSURE OF EARTH FILLS MEASURED[1]

By C. N. CONNER, State Construction Engineer, North Carolina State Highway Department

Clay fill at 13-foot level

Scales in place in culvert

VALUABLE data on the vertical pressure of earth fills of various materials are expected to result from experiments now being conducted by the University of North Carolina in cooperation with the North Carolina State Highway Commission.

The curves in Figure 1 show the results of some of the early experiments with sand and clay fills. It is interesting to note that greater pressures are brought to bear on the 30-inch cast-iron pipe by the clay fill than the sand fill at all depths.

The experiments are being conducted under the direction of G. M. Braune, dean of the School of Engineering, University of North Carolina, and P. K. Schuyler, associate professor of highway engineering, is actively supervising the work. The plans for the weighing scales and the general methods in use were suggested and approved by A. T. Goldbeck, chief, division of tests, United States Bureau of Public Roads.

The methods used to determine the pressures are as follows: Four 2½-foot sections of 30-inch cast-iron pipe were placed on columns, which rested on the weighing platforms of specially designed scales. The scales and columns were housed in a concrete culvert, in the top of which there was a slot just large enough to admit the pipe, which lay in a horizontal position, with one half of its surface protuding above the top of the culvert and exposed to the pressure of the earth fill, while the other half of its surface was inside the culvert resting on the top of the column.

A sand fill, using uniform quality of sand, was built up in 1-foot layers, each layer being carefully leveled off and the pressures accurately determined by weighing the loads on the various scales. An attempt was made to roll the sand fill, but it was not found to be practicable. The experimental fill with sand was carried to a height of 20 feet above the top of the pipe. The sand fill was then removed and replaced with a clay fill. This fill was also placed in 1-foot layers and readings taken at each foot level in a manner similar to the method employed with the sand fill. The clay fill was rolled with a 4-ton roller and carried to a height of 14 feet. The next part of the experiment as proposed will consist of using a clay fill and laying the pipe in a trench excavated after the fill is made. It is believed that by laying a pipe in this manner the pressure exerted on it by the fill is lessened.

Maj. William Cain, an authority on earth pressure, has suggested certain laboratory experiments, which are being carried out in connection with the field work. It is thus hoped to obtain data on the coefficients of friction and cohesion of soils, which can be applied to the results obtained in the field and thereby add to the present available information on the subject of earth pressure.

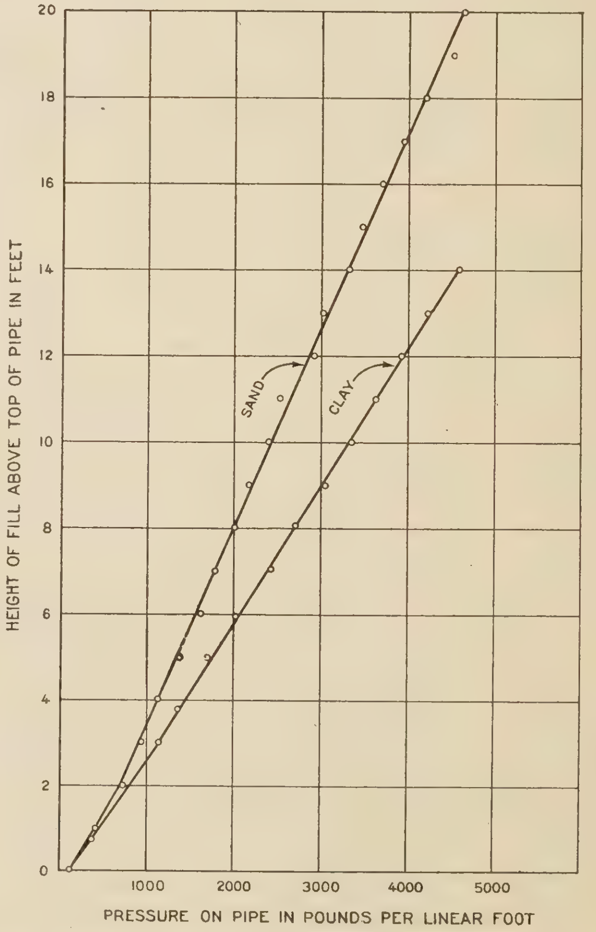

FIG. 1.—Pressures produced by sand and clay fills on 30-inch cast-iron pipe

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[1] Submitted for publication through the Highway Research Board of the National Research Council.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL AID HIGHWAY CONSTRUCTION

AS OF

FEBRUARY 28, 1925

GOVERNMENT PRINTING OFFICE

STATES	FISCAL YEARS 1917-1924			FISCAL YEAR 1925									BALANCE OF FEDERAL AID FUND AVAILABLE FOR NEW PROJECTS	STATES
	PROJECTS COMPLETED PRIOR TO JULY 1, 1924			PROJECTS COMPLETED SINCE JUNE 30, 1924			*PROJECTS UNDER CONSTRUCTION			PROJECTS APPROVED FOR CONSTRUCTION				
	TOTAL COST	FEDERAL AID	MILES	TOTAL COST	FEDERAL AID	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES		
Alabama	$ 4,598,721.63	$ 2,186,247.54	464.1	$ 1,211,826.12	$ 597,175.34	132.2	$ 14,988,146.68	$ 7,263,473.51	802.8	$ 79,416.15	$ 39,708.07	0.4	$ 2,708,228.54	Alabama
Arizona	8,338,365.41	4,287,683.88	527.8	713,173.87	406,825.70	37.5	1,985,482.12	1,203,724.85	169.2	666,410.72	407,243.56	51.6	2,246,394.01	Arizona
Arkansas	11,094,751.31	4,424,345.63	944.4	1,637,568.79	688,383.74	68.1	7,077,064.30	2,975,484.70	382.0	390,704.48	154,050.66	22.2	2,084,299.27	Arkansas
California	12,999,075.03	5,647,148.17	533.7	6,134,843.27	3,307,620.89	257.3	10,534,164.28	5,239,754.58	276.9	14,898.29	8,789.99		5,362,628.37	California
Colorado	8,108,070.31	4,029,898.97	502.6	1,578,787.09	829,849.40	71.3	4,982,544.65	2,688,816.09	202.4	476,373.92	177,583.34	11.1	3,206,971.20	Colorado
Connecticut	3,062,872.02	1,269,559.60	73.6	199,024.56	98,423.00	4.9	3,262,054.48	1,045,804.04	54.1				1,442,210.36	Connecticut
Delaware	3,056,832.22	1,007,714.83	72.5	951,730.50	380,775.82	27.4	785,048.44	321,281.10	19.5				395,383.25	Delaware
Florida	961,134.07	461,470.92	48.8	1,840,381.57	894,017.05	40.4	8,206,935.44	3,971,175.98	231.9	506,722.44	190,336.40	11.5	1,662,764.65	Florida
Georgia	17,167,373.32	7,955,805.20	1,214.2	1,890,830.71	916,025.00	169.5	11,397,917.44	5,350,291.47	777.0	367,074.37	128,236.68	34.9	2,082,627.65	Georgia
Idaho	8,181,697.92	4,092,395.52	506.8	1,025,866.02	584,588.92	68.4	1,883,697.06	1,160,646.54	129.9	590,256.73	397,532.32	43.9	1,379,475.70	Idaho
Illinois	26,964,706.06	12,279,546.33	804.7	4,724,921.20	2,320,686.26	152.4	12,467,692.53	6,188,330.64	428.8				5,839,407.77	Illinois
Indiana	7,577,444.16	3,655,540.97	225.7	3,847,801.03	1,846,705.95	130.6	13,309,694.44	6,513,176.10	428.3				4,235,661.98	Indiana
Iowa	23,195,778.19	9,237,031.86	1,682.9	2,995,755.18	1,367,916.81	228.1	6,154,529.09	2,793,411.59	439.9	2,862,077.21	1,202,126.05	105.3	2,806,046.69	Iowa
Kansas	17,084,136.48	6,043,176.80	502.7	6,634,089.23	2,611,801.08	228.5	13,887,101.93	5,650,610.41	575.0	2,476,897.02	976,253.63	120.5	2,091,807.08	Kansas
Kentucky	10,822,980.31	4,613,947.28	429.4	2,635,711.90	1,052,626.11	99.2	8,028,739.26	3,646,720.51	298.9	406,326.77	140,280.00		2,329,772.10	Kentucky
Louisiana	8,488,463.18	3,636,143.36	661.2	1,796,469.94	876,444.77	151.8	4,508,500.61	2,245,730.04	260.4	118,433.78	59,216.89	0.5	1,446,168.94	Louisiana
Maine	6,911,058.78	3,299,935.38	230.7	1,263,222.53	607,934.95	50.7	749,878.17	350,363.39	24.2				1,516,878.28	Maine
Maryland	6,760,044.42	3,213,321.78	243.2	646,410.32	307,486.47	25.5	2,464,768.03	1,065,404.17	76.2	166,738.11	55,650.00	4.2	642,870.58	Maryland
Massachusetts	10,191,202.02	4,105,727.22	232.8	565,949.13	184,277.95	9.8	6,131,750.58	1,967,428.71	100.2	1,519,848.77	426,439.71	25.4	2,326,024.41	Massachusetts
Michigan	13,434,135.07	6,060,612.23	494.5	2,030,127.09	928,663.92	85.8	14,828,927.22	7,004,292.58	491.8	163,170.00	81,585.00	5.4	4,029,845.27	Michigan
Minnesota	24,037,561.24	9,885,843.07	2,292.0	6,378,124.65	2,852,798.97	429.2	6,294,034.56	2,526,600.00	650.8	679,082.36	46,300.00	67.8	2,131,027.96	Minnesota
Mississippi	7,888,193.89	3,828,941.39	655.0	1,840,746.14	881,221.43	136.4	8,318,899.13	4,180,193.92	481.1	205,237.88	102,618.94	13.3	1,830,257.32	Mississippi
Missouri	11,352,027.70	5,245,899.18	803.5	3,418,813.73	1,691,588.82	186.6	23,530,361.95	9,699,116.19	805.9	4,475,883.97	897,994.12	166.7	2,823,316.69	Missouri
Montana	8,867,279.16	4,384,335.12	791.4	1,240,143.42	907,104.11	127.3	1,935,343.45	1,406,802.11	164.3	1,038,200.22	590,707.66	117.2	5,225,941.00	Montana
Nebraska	7,876,337.16	3,714,691.59	1,440.4	552,451.12	263,623.02	32.0	8,329,203.67	4,082,797.91	902.5	365,085.32	182,542.65	35.2	4,789,259.83	Nebraska
Nevada	3,460,245.52	1,853,624.98	225.6	1,446,557.71	1,228,225.07	131.4	4,300,066.51	3,622,200.69	361.5				1,134,346.26	Nevada
New Hampshire	3,076,750.19	1,487,867.58	171.3	976,255.13	453,342.53	35.0	855,015.12	401,745.62	25.8	40,305.73	19,027.23	1.6	438,606.04	New Hampshire
New Jersey	7,623,795.12	2,661,531.49	148.7	3,474,504.68	921,087.99	55.4	7,297,701.96	2,277,518.25	40.1				1,664,191.27	New Jersey
New Mexico	5,306,286.45	2,758,849.68	714.3	1,897,320.22	1,216,549.20	196.8	5,677,646.65	3,719,421.07	554.5	250,983.39	154,354.77	16.7	1,925,323.28	New Mexico
New York	18,862,742.49	8,257,844.44	572.7	2,048,366.93	841,486.31	57.9	30,373,274.84	11,391,189.38	676.0	5,738,088.00	1,690,100.00	109.7	8,184,623.87	New York
North Carolina	12,567,732.97	5,676,757.66	884.7	5,596,875.90	2,019,346.21	156.7	6,998,334.85	2,816,788.84	194.6	2,077,691.35	925,978.97	58.6	2,554,547.32	North Carolina
North Dakota	9,088,973.11	4,418,505.42	1,587.9	1,538,510.56	751,591.33	304.8	2,668,572.13	1,339,895.23	367.9	390,407.61	195,203.76	33.6	2,839,159.26	North Dakota
Ohio	33,122,751.43	11,879,917.99	962.5	7,315,479.45	2,996,275.94	198.2	8,675,542.09	3,008,307.50	253.1	2,461,465.64	924,794.15	72.3	4,120,456.42	Ohio
Oklahoma	12,986,865.26	5,888,852.03	497.3	5,198,375.46	2,515,773.32	216.9	6,819,841.25	3,181,417.71	325.0	1,072,902.56	446,501.55	70.7	2,259,263.39	Oklahoma
Oregon	12,082,873.17	5,819,093.79	655.6	1,209,085.39	707,463.39	95.4	3,385,451.57	1,963,099.34	150.5				1,196,170.48	Oregon
Pennsylvania	36,825,248.98	14,114,694.79	729.7	2,621,735.82	1,034,703.38	56.5	22,289,117.00	5,881,352.50	364.1	9,699,397.38	3,392,560.00	225.8	3,538,428.33	Pennsylvania
Rhode Island	1,774,397.25	779,227.96	46.0	854,098.95	340,460.13	18.8	1,171,551.79	341,168.84	15.8	248,821.10	86,175.00	5.7	751,634.07	Rhode Island
South Carolina	9,016,476.73	4,124,045.22	924.4	1,751,203.47	810,291.65	269.6	6,165,301.24	2,330,703.22	402.5	463,013.22	112,074.48	9.4	1,362,980.43	South Carolina
South Dakota	8,674,597.86	4,244,636.27	989.8	2,807,897.50	1,465,555.64	424.5	6,222,192.74	2,937,305.56	803.5	220,684.20	4,000.00	45.5	1,282,202.53	South Dakota
Tennessee	6,805,683.35	3,313,936.07	259.6	5,564,284.08	2,752,118.58	192.5	11,702,655.73	5,293,372.60	422.4	677,750.73	338,876.36	37.1	1,949,319.39	Tennessee
Texas	42,341,998.56	16,190,624.91	3,122.8	7,749,029.67	3,130,057.52	505.0	23,982,053.14	9,991,360.29	1,462.8	3,895,293.86	1,792,562.98	254.3	5,035,322.30	Texas
Utah	3,304,423.75	1,895,805.92	219.0	1,379,283.77	875,315.41	130.5	4,144,168.50	2,721,727.32	242.3	338,709.28	236,839.03	31.5	1,233,252.32	Utah
Vermont	1,922,114.16	942,769.12	74.4	347,337.97	162,957.67	9.6	1,939,138.59	929,470.01	49.6	10,699.53	5,349.76		859,057.44	Vermont
Virginia	10,035,301.48	4,801,782.43	562.5	1,670,046.39	792,999.52	67.7	10,109,396.38	4,667,709.01	346.6	759,458.11	315,078.77	31.0	1,465,096.27	Virginia
Washington	11,384,615.67	5,290,895.45	457.0	1,172,750.16	511,294.59	51.9	3,367,073.68	1,599,900.00	134.9	296,296.71	134,000.00	9.1	1,469,574.96	Washington
West Virginia	5,489,747.95	2,365,041.53	255.6	1,853,452.91	865,251.90	71.1	4,166,291.65	1,791,537.78	127.9	125,835.05	51,815.75	5.1	1,477,780.14	West Virginia
Wisconsin	18,753,903.15	7,441,033.57	1,325.3	2,196,436.45	1,064,453.60	92.5	3,175,101.72	1,516,853.95	139.2	53,417.25	26,708.00	3.9	5,512,709.98	Wisconsin
Wyoming	6,127,625.61	3,078,098.70	687.6	2,253,839.73	1,385,969.97	254.8	3,140,910.64	1,959,362.40	157.9	86,301.49	55,793.00	8.4	1,143,073.93	Wyoming
Hawaii													731,250.00	Hawaii
TOTALS	549,655,391.27	237,852,399.92	32,452.9	120,677,497.41	56,237,136.23	6,544.4	374,668,879.28	166,224,837.14	16,791.4	46,476,360.70	17,172,988.23	1867.1	120,762,638.58	TOTALS

* Includes projects reported completed (final vouchers not yet paid) totaling: Estimated cost $ 113,536,994.31 Federal aid $ 50,031,036.03 Miles 4,446.9

MOTOR VEHICLE REGISTRATION AND REVENUES, REGISTRATION YEAR 1924

State	Individually and commercially owned				Official cars and trucks owned by State, etc.[1]	Motor-cycles	Registration fees, licenses, permits, etc.		Amount of registration fees paid for		Grand total motor cars 1923	Per cent increase during 1924	State
	Grand total motor cars 1924[1]	Passenger cars[1]	Motor trucks[1]	Taxis, busses, and cars for hire			Total gross receipts	Amount applicable to highway work by or under supervision of State highway department	Passenger cars	Motor trucks			
												Per cent	
Alabama	157,262	135,777	18,688	2,797	(2)	549	$1,954,801	$1,581,047			126,642	24.2	Alabama.
Arizona	57,828	50,233	7,595	(3)	903	372	339,722	339,722			49,175	17.6	Arizona.
Arkansas	141,983	125,368	16,615	(3)	458	295	2,333,240	1,833,240	$1,980,814	$262,317	113,300	25.3	Arkansas.
California	1,319,394	1,125,381	[4] 194,013	(4)	(3)	12,325	7,011,113	3,079,659	3,594,636	2,440,377	1,100,283	19.9	California.
Colorado	213,247	197,361	15,886	(5)	(2)	2,226	1,258,205	574,568	992,333	180,222	188,956	12.9	Colorado.
Connecticut	217,227	180,542	33,776	2,909	1,110	4,211	5,069,581	5,069,581	2,766,530	1,047,278	181,748	19.5	Connecticut.
Delaware	35,136	29,075	6,061	(3)	(3)	325	604,354	604,354	334,250	122,874	29,977	17.2	Delaware.
District of Columbia	88,762	78,846	9,916	(5)	1,351	1,889	378,868				[6] 74,811	18.6	District of Columbia.
Florida	195,128	157,519	34,192	3,417	(3)	733	2,418,933	1,576,118			151,990	28.4	Florida.
Georgia	207,688	181,268	26,275	145	(3)	750	2,532,266	2,446,215	2,067,280	408,823	173,889	19.4	Georgia.
Idaho	69,227	61,600	7,627	(3)	930	619	1,306,892	326,723	1,083,700	195,727	62,379	11.0	Idaho.
Illinois	1,119,236	978,428	140,808	(3)	(3)	6,873	11,546,206	11,546,206			969,331	15.5	Illinois.
Indiana	651,705	566,736	84,969	(3)	(3)	4,822	4,102,666	3,906,858	3,030,023	826,008	583,342	11.7	Indiana.
Iowa	616,128	575,210	40,918	(5)	2,400	2,597	8,979,170	[7] 8,171,045			571,061	7.9	Iowa.
Kansas	410,891	370,951	39,940	(2)	1,947	1,632	[7] 4,222,930	[7] 4,036,937			375,594	9.4	Kansas.
Kentucky	229,804	206,064	23,275	[8] 465	1,044	724	3,233,379	3,108,732			198,377	15.8	Kentucky.
Louisiana	[7] 178,000	[7] 150,900	[7] 27,100	(5)	1,000	510	2,790,348	2,790,348	[7] 1,922,716	[7] 813,000	136,622	30.3	Louisiana.
Maine	127,178	105,040	19,001	3,137	854	1,288	1,933,561	1,839,269			108,609	17.1	Maine.
Maryland	198,398	184,398	11,183	2,817	(3)	3,462	2,332,953	1,633,067	1,399,020	247,295	169,351	17.2	Maryland.
Massachusetts	[1] 570,578	[1] 486,952	[1] 83,626	(5)	[9] 900	10,778	8,122,166	[7] 7,400,000	5,119,148	1,233,626	[1] 479,909	18.9	Massachusetts.
Michigan	867,545	784,070	83,475	(3)	(3)	3,644	12,404,546	5,638,050	9,730,255	1,408,579	730,658	18.7	Michigan.
Minnesota	503,437	465,165	37,823	449	2,171	3,080	8,591,853	8,591,853	7,387,698	886,036	448,187	12.3	Minnesota.
Mississippi	134,680	122,117	12,563	(5)	(2)	96	1,525,077	589,844			104,286	29.1	Mississippi.
Missouri	540,500	489,356	51,144	(5)	1,203	2,139	4,525,914	4,238,914			476,598	13.4	Missouri.
Montana	79,695	69,824	9,871	(3)	979	293	776,320		638,534	107,310	73,828	7.9	Montana.
Nebraska	308,715	277,449	31,266	(2)	(3)	1,342	3,597,261	[7] 2,697,946	2,922,756	564,702	286,053	7.9	Nebraska.
Nevada	18,118	16,236	1,882	(5)	336	111	181,970	172,000	142,528	34,168	15,699	15.4	Nevada.
New Hampshire	70,932	63,662	7,270	(3)	(2)	1,750	1,522,186	1,411,794			59,604	19.0	New Hampshire.
New Jersey	504,217	393,785	99,288	11,144	[7] 4,200	8,053	9,278,428	8,213,182	3,673,989	2,701,805	430,958	17.0	New Jersey.
New Mexico	41,680	39,890	1,790	(3)	(3)	228	421,412	400,342			32,032	30.1	New Mexico.
New York	1,412,879	1,136,678	236,012	40,189	8,910	19,837	24,089,241	18,066,930	14,001,939	6,235,099	1,204,213	17.3	New York.
North Carolina	302,232	272,552	27,480	2,200	(3)	1,029	4,614,521	4,153,069			[10] 246,812	22.5	North Carolina.
North Dakota	117,346	112,664	4,682	(3)	[9] 317	509	816,766	[11] 773,691			109,266	7.4	North Dakota.
Ohio	1,241,600	1,076,800	164,800	(3)	5,400	15,000	11,685,329	5,842,664			1,069,100	16.1	Ohio.
Oklahoma	369,903	342,856	27,047	(3)	(3)	733	3,728,679	[12] 3,323,609			307,000	20.5	Oklahoma.
Oregon	192,615	177,558	15,057	(3)	(3)	2,764	4,766,070	3,424,552	3,925,444	688,712	165,962	16.1	Oregon.
Pennsylvania	1,228,587	1,043,692	178,122	6,773	(3)	17,540	22,107,376	22,107,376	10,236,151	4,870,202	1,043,770	17.7	Pennsylvania.
Rhode Island	95,482	76,666	17,247	1,569	(3)	1,428	1,623,604	[7] 1,523,604	935,586	370,886	76,312	25.1	Rhode Island.
South Carolina	161,753	146,639	15,114	(3)	1,067	477	1,151,983	921,586	933,463	192,154	127,467	26.9	South Carolina.
South Dakota	142,396	131,190	11,206	(3)	(3)	305	2,068,437	1,445,920			131,700	8.1	South Dakota.
Tennessee	204,680	183,891	20,789	(3)	(3)	682	2,597,870	2,597,870	2,021,931	534,079	173,365	18.1	Tennessee.
Texas	801,712	735,270	62,754	3,688	(2)	2,634	10,373,997	7,225,991			688,233	16.5	Texas.
Utah	68,316	59,453	8,863	(3)	500	731	485,969	427,509	379,972	87,992	59,525	14.8	Utah.
Vermont	[13] 61,179	[13] 57,072	[13] 4,107	(3)	123	779	1,323,377	1,252,101	1,008,165	101,452	52,776	15.9	Vermont.
Virginia	261,945	220,000	41,643	302	(3)	3,000	3,791,556	3,791,556			218,896	19.7	Virginia.
Washington	295,443	251,466	41,555	2,422	3,701	3,164	4,861,420	4,416,053	3,260,688	950,127	258,264	14.4	Washington.
West Virginia	190,734	163,907	22,171	4,656	(3)	1,407	2,874,587	2,332,712	1,949,982	449,016	157,924	20.8	West Virginia.
Wisconsin	525,221	475,182	50,039	(3)	3,005	3,938	6,786,485	[7] 6,500,000	5,483,275	1,160,967	457,271	14.8	Wisconsin.
Wyoming	43,639	38,831	4,808	(3)	177	252	448,664	448,664	346,365	90,622	39,831	9.6	Wyoming.
Total	17,591,981	15,371,570	2,131,332	89,079	44,986	153,925	225,492,252	184,393,071	93,269,171	29,211,455	15,090,936	16.6	Total.

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[1] Net number of cars and trucks shown when possible, excluding reregistrations and nonresident registrations. Federal, State, or other Government owned cars and trucks, not registered and not paying licenses, are also excluded in grand totals, unless noted.

[2] Recorded in private cars and trucks.

[3] Not separately recorded.

[4] "Motor trucks" includes solid and pneumatic types, also taxis, busses, etc.

[5] Included with private passenger cars.

[6] Reregistrations included, but nonresident excluded.

[7] Approximate.

[8] City cabs excluded.

[9] State owned cars only.

[10] First six months of registration year only.

[11] Excludes cost of motor registration department.

[12] To be expended by counties under general regulation made by State highway department

[13] Includes nonresident registrations.